STRATEGIES TO OPTIMIZE PASTURE SUPPLEMENTATION SYSTEMS

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INTRODUCTION

After about a decade living in South America, Jean Baptiste Boussingault returned to his native France in 1832. Thirteen years later, the "founder of scientific agriculture" (McCollum, 1957) published a major treatise on his investigations into subjects as varied as the germination of wheat to the influence of agricultural activities on global climate change (Boussingault, 1850). Among his numerous notable contributions to agricultural and nutritional sciences, in this work, Boussingault reported results from a variety of feeding studies in which he evaluated what we might now call replacement values of feedstuffs. In assessing the nutritive values of various feedstuffs, Boussingault first recognized the utility of comparing feeds to some defined 'feeding standard', and secondly, realized the futility of attempting to measure responses to every possible combination of different feedstuffs. It was this recognition, and the advancements in chemistry occurring during his time that led to his development of perhaps the first table of chemical composition of feedstuffs (Figure 1). Boussingault recognized that dealing with feedstuffs as discrete entities (e.g. oats vs. potatoes vs. beets, etc.) was not conducive to drawing generalizations about the nutritive value of the various feedstuffs. He realized that knowledge of the chemical makeup of these substances was necessary to permit an understanding, and prediction, of the replacement value of one feedstuff for another. Nearly 200 years later, we stand on the shoulders of such giants and see how far we have come. Often, however, this perspective distorts our view of how little progress has been made in some areas . Though the idea of comparing feedstuffs based on their chemical composition is now recognized as fundamental to all areas of nutrition, to a large extent, the body of scientific knowledge regarding forage supplementation is still one of discrete entities. There are myriad studies comparing supplement "x" against supplement "y" with forage base "z", yet precious little work providing cohesive generalizations to enhance our understanding and predictive ability. In this paper, I argue that our *best strategy for optimizing pasture supplementation systems* is to facilitate the

development of models within which we can understand and predict responses to supplements used in forage-based systems. We each have our own role to play in this process: the producers to provide us with the right questions to ask; the field researchers to provide the quantitative data necessary for model development; the laboratory researchers to identify nutritionally meaningful constituents and provide the tools to measure them; and the modelers, to develop and validate the models. Within this context, I also hope to point out areas in which we can make generalizations with a fair degree of confidence based on the current knowledge, and which should facilitate the optimization of supplementation systems.

OPTIMIZATION

Optimization is not maximization. Often, in agricultural research, our business has been to maximize some response criteria, and, toward this end, we have often been imminently successful. One has only to look at the changes in "efficiency" of livestock production across the last 50 years as evidence of this. However, the whole concept of supplementation is somewhat contradictory to the idea of maximization. Generally, supplementation connotes provision of nutrient-dense feedstuffs to animals consuming some basal, forage-based diet. If maximization of growth, or maximizing efficiency of growth, were our target – we would abandon the forage component and focus on providing the bulk of the diet as nutrient-dense feedstuffs. One could argue that our ultimate goal is to maximize economic efficiency, yet this is not always the only goal in pastoral systems. In fact, many would argue that economic efficiency is only critical as one component of the sustainability of forage-based livestock production. Increasingly, our interests in supplementation of forage-fed livestock are concerned with sustainability and ecological implications. How will we impact our forage base? How will we impact nutrient cycling into the environment? Though these types of questions are critical, as are questions of economics, I will not deal with them directly in this paper. The answers to these types of questions are typically very locally and/or temporally specific. Two years ago in Kentucky, corn was less than $2.00/bushel and was a viable pasture supplement. Today, with prices in excess of $5.00/bushel, there is little interest in the efficiency of gains with supplemental corn. Thus, the focus in this paper is on the larger, global issues that can be used as tools to help answer questions about optimization at a local level.

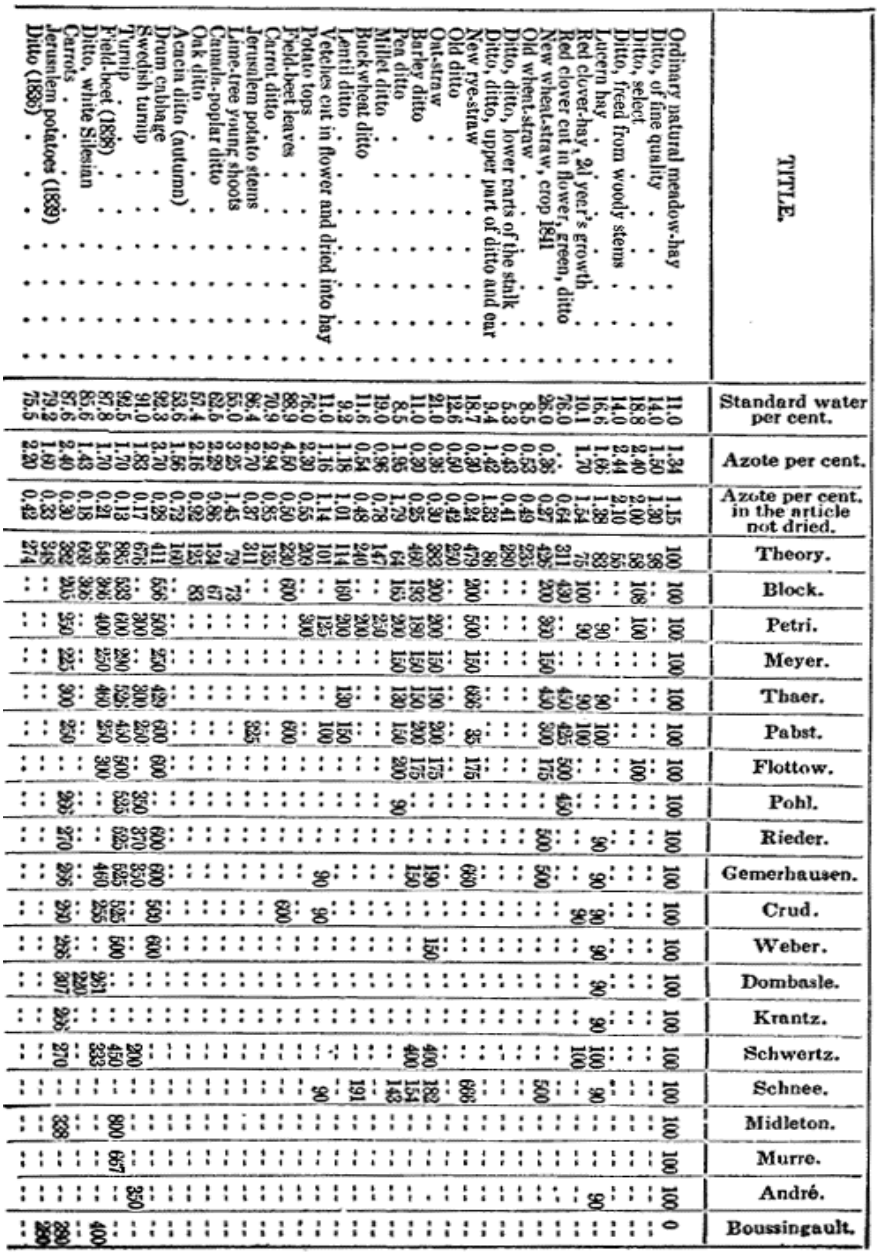

TABLE OF THE NUTRITIVE EQUIVALENTS OF DIFFERENT KINDS OF FORAGE.

TITLE.	Standard water per cent.	Azote per cent.	Azote per cent. in the article not dried.	Theory.	Block.	Petri.	Meyer.	Thaer.	Pabst.	Flottow.	Pohl.	Rieder.	Gemerhausen.	Crud.	Weber.	Dombasle.	Krantz.	Schwertz.	Schnee.	Midleton.	Murre.	André.	Boussingault.
Ordinary natural meadow-hay	11.0	1.34	1.15	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
Ditto, of fine quality	14.0	1.50	1.30	98	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
Ditto, select	18.8	2.40	2.00	68	108	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
Ditto, freed from woody stems	14.0	2.44	2.10	55	83	90	100	90	100	100	100	100	100	100	100	100	100	100	100	100	100	100	0
Lucern hay	16.6	1.69	1.38	83	100	90	100	90	100	100	100	100	100	100	100	100	100	100	90	100	100	90	0
Red clover-hay, 2d year's growth	10.1	1.70	1.54	75	100	90	100	90	100	100	100	90	100	100	90	100	100	100	100	100	100	100	0
Red clover cut in flower, green, ditto	76.0	0.36	0.64	311	430	200	150	450	300	175	450	500	500	500	500	500	500	500	500	500	500	500	0
New wheat-straw, crop 1841	26.0	0.37	0.27	425	200	300	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Old wheat-straw	8.5	0.53	0.49	233	280	200	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Ditto, ditto, lower parts of the stalk	5.3	0.43	0.41	280	200	300	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Ditto, ditto, upper part of ditto and ear	9.4	1.42	1.33	88	200	300	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
New rye-straw	18.7	0.30	0.24	479	500	500	150	600	350	175	450	600	600	600	600	600	600	600	600	600	600	600	0
Old ditto	12.6	0.50	0.42	250	200	300	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Oat-straw	21.0	0.36	0.30	383	200	300	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Barley ditto	11.0	0.20	0.25	493	183	180	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Pea ditto	8.5	1.95	1.79	64	165	200	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Millet ditto	19.0	0.96	0.78	147	200	250	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Buckwheat ditto	11.6	0.54	0.49	240	200	200	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Lentil ditto	9.2	1.18	1.01	114	160	200	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Vetches cut in flower and dried into hay	11.0	1.16	1.14	101	200	125	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Potato tops	76.0	2.39	0.55	200	300	300	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Field-beet leaves	88.9	4.60	0.60	230	600	600	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Carrot ditto	70.9	2.94	0.55	135	600	600	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Jerusalem potato stems	86.4	2.70	0.37	311	600	600	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Lime-tree young shoots	55.0	3.25	1.45	79	73	67	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Canada-poplar ditto	62.6	2.29	0.86	134	67	83	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Oak ditto	57.4	2.16	0.92	135	83	100	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Acacia ditto (autumn)	53.6	1.56	0.72	160	556	300	150	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Drum cabbage	92.3	3.70	0.73	411	500	600	250	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Swedish turnip	91.0	1.83	0.98	676	556	400	250	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Turnip	92.5	1.70	0.17	883	533	600	250	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Field-beet (1838)	87.8	1.70	0.13	548	533	600	250	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Ditto, white Silesian	85.6	1.43	0.21	638	533	400	250	450	450	500	450	600	600	600	600	600	600	600	600	600	600	600	0
Carrots	87.6	2.40	0.30	382	205	250	225	300	250	300	250	600	600	600	600	600	600	600	600	600	600	600	0
Jerusalem potatoes (1839)	79.2	1.60	0.33	348	205	250	225	300	250	300	250	600	600	600	600	600	600	600	600	600	600	600	0
Ditto (1836)	75.5	2.20	0.42	274	205	250	225	300	250	300	250	600	600	600	600	600	600	600	600	600	600	600	0

Figure 1 - Boussingault's table of water and N (azote) content of feedstuffs (image copied from Boussingault, 1850).

What are these global issues that we should focus on? One could argue that the point of supplementation is to sustain some desired level of animal production. Perhaps, when grazing on forage alone, cattle will only gain 0.5 kg/d, and, given local market and economic considerations, it would be desirable for them to gain 1.0 kg/d. Thus, the producer's interest is the ability for a given quantity of supplement to sustain a given level of gain, the partial efficiency of the supplement. Though this is ultimately our goal, I believe that for the purposes of providing a general model with reasonable prediction accuracy, direct prediction of gain is at too high a level of aggregation. In other words, we know that there are many factors that can impinge on a supplement's ability to provide a certain level of gain. Attempting to explain responses in gain without attention to some of the 'lower-level' factors, is subject to a large degree of error. At the other extreme, I believe there are factors that we routinely measure which help provide mechanistic explanations of responses to supplements that exist at too low a level of aggregation to be of predictive benefit. Ruminal fermentation characteristics, for example, can help provide understanding of why a particular dietary strategy produces the response that it does, but our current level of knowledge makes it difficult to use such information in a predictive manner. In other words, I can predict that a given level of a starch based supplement will produce a particular ruminal pH, but it is very difficult to predict exactly how that pH will translate into changes in nutrient supply for the animal. Thus, given the current state of scientific understanding, it is arguable that the most meaningful response criteria to assess are effects of supplementation on forage intake and diet digestibility. The majority of the variation in animal performance (e.g., growth rate in growing animals, body condition score changes in mature animals) is explained by variation in digestible dry matter intake. We know that current nutritional models, such as the NRC (1996) model, can provide reasonably accurate measures of animal performance, provided we have accurate measures of nutrient intakes and digestibilities to use as model inputs. Certainly, with forage-fed, and particularly with grazing scenarios, obtaining accurate measures of intake and digestibility can be a challenge. This challenge is compounded when we introduce supplemental nutrients, because additivity with supplements is a rare, if not nonexistent, occurrence. Almost without exception, provision of supplements either stimulates or retards forage intake and/or digestibility. Nonetheless, it is my argument that the greatest gains in

development of optimal supplementation systems will occur as a result of our ability to predict effects of supplements on forage intake and diet digestibility.

WHY SUCH A DIFFICULT PROBLEM?

There are many reasons that, nearly 200 years after Boussingault, we still struggle with a “unified theory” of supplementation. Perhaps most importantly, this is an issue associated with forage-fed animals. There is no classification of feedstuffs that is more diverse from a nutrient content standpoint. Response to a given supplement will be vastly different if the forage base is a highly lignified, 4% crude protein (CP) weathered C4 grass, as compared with a vegetative, growing legume containing in excess of 20% CP. One of the first issues that must be addressed when attempting to optimize a supplementation strategy is the identification of the limiting nutrients in the basal forage. This task is complicated by the fact that we are dealing with ruminant animals, so we must consider nutrients that might limit microbial growth as well as nutrients that may be limiting to the host animals. Also, because of the tremendous variation in byproducts that are well suited to serve as supplements for ruminant animals, we are faced with a myriad of possible substrate interactions between supplement and forage components. Additionally, optimization will depend upon the goals of the manager. There are many potential reasons for providing supplemental nutrients. As nutritionists, we are often focused on providing supplements to complement the basal forage, either by enhancing its intake level, digestibility, or both (i.e. the need to identify the limiting nutrients). However, situations exist in which supplements are provided to stretch a limited forage supply, in which case large substitutions of supplement intake for forage intake may be advantageous. In other situations, one may wish to provide specific nutrients that may serve some specific physiological role at a key time (e.g. strategic use of polyunsaturated fatty acids to enhance reproductive performance of cows). Other reasons for supplementation are less researched. These would include potential health effects (more frequent observation would be expected to lead to more effective treatment and supplements provide opportunities to deliver oral therapeutic agents), opportunities to control grazing distribution, particularly in expansive grazing situations, and other ancillary benefits, including, but not limited to the possibility of decreased live weight shrink when gathering calmer, more-easily-

handled animals from pasture. These various management goals further complicate the question of what an optimal supplementation strategy consists of. Additionally, we have only begun to scratch the surface of understanding how various substrates interact within the GI tract of ruminant animals. Such interactions can have profound influence on nutrient utilization and animal performance. When working with supplementation, we are, by definition, creating situations in which we hope to capitalize on beneficial interactions among nutrients and to minimize detrimental ones.

IDENTIFYING LIMITING NUTRIENTS

On its surface, it would appear that the identification of protein vs. energy as the first limiting nutrient on a given forage would be a fairly straight forward assignment. However, not until the last decade or so have we had the tools to begin quantitatively differentiating between the two. With low-quality forages, we typically have deficiencies of both protein and digestible energy. Typically, animals consuming such forages would display classical signs of energy deficiency – loss of body weight and condition, poor reproductive performance, etc. Thus, it has long been common practice to provide high energy (often starch-based) supplements to remedy such situations. However, failure to recognize the energy deficiency as secondary to a degradable protein deficiency can lead to failure of supplements to achieve the desired effects. In spring-calving beef cows (464 kg initial weight) consuming low-quality (3.4% CP, 57.0% NDF) forage sorghum hay, increasing the amount of supplemental energy from about 3.5 to 6.9 Mcal ME/day in sorghum grain/soybean meal supplements actually decreased third-trimester weight gains (Figure 2) and body condition score gains (data not shown; Vanzant and Jaeger, 1995). Though these cows were deficient in energy, provision of high levels of starch exacerbated an already existing degradable intake protein (DIP) deficiency. Thus, responses to supplementation with a degradable protein source (soybean meal) were dramatic, and had residual effects that were measured 257 days after discontinuation of the supplementation treatments.

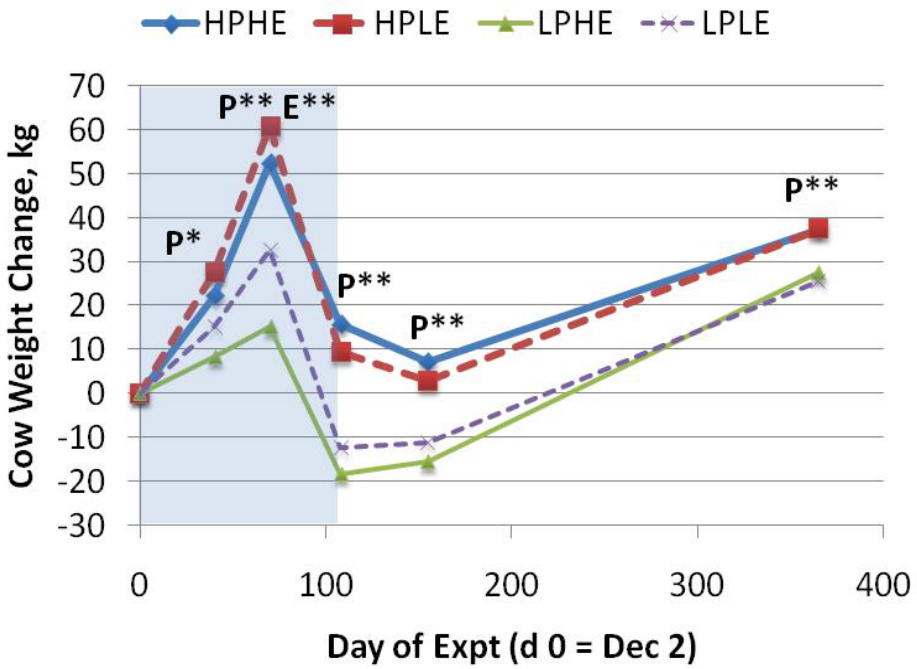

Figure 2 - Cow weight change in response to protein and energy supplements provided over the third trimester (shaded region) of gestation to cows consuming low quality forage sorghum hay. Sorghum grain/soybean meal supplements: HPHE = high protein/high energy (.45 kg CP and 6.9 Mcal ME·d^{-1}); HPLE = high protein/low energy (.45 kg CP and 3.5 Mcal ME ·d^{-1}); LPHE = low protein /high energy (.23 kg CP and 6.9 Mcal ME·d^{-1}); LPLE = low protein/low energy (.23 kg CP and 3.5 Mcal ME·d^{-1}. P* = protein effect (P < 0.10); P** = protein effect (P < 0.05); E** = energy effect (P < 0.05) (Vanzant and Jaeger, 1995).

SUPPLEMENTATION WITH DEGRADABLE PROTEIN

Degradable intake protein can increase the energy status of cows because it supplies the primary limiting nutrient for ruminal microorganisms. Thus, the NRC(1996) proposed using measures of

microbial growth efficiency as a criterion for establishing 'requirements' for DIP. However, any connection between microbial growth efficiency and animal performance is indirect. Of more direct influence on the animal are the depressions seen in forage intake and digestibility subsequent to DIP deficiencies. Thus, the approach taken by Koster et al. (1996) provides a more useful measure of DIP requirements. In this approach, DIP requirements are expressed relative to the threshold response in digestible organic matter intake (DOMI), which is an integrated measure of voluntary forage intake and digestibility (Figure 3). In that study with low quality warm season grass hay, microbial efficiency increased in a linear manner throughout the range of DIP used, substantiating a disconnect between the point at which we would determine DIP optima based on microbial efficiency as compared with DOMI. Mathis et al. (2000) used this approach in an attempt to determine DIP requirements for three diverse, low-quality forages. In that work, DIP levels that provided maximal DOMI varied widely for bermudagrass (8.2% of DOM), bromegrass (9.8% of DOM) and forage sorghum (12.8% of DOM) hays, all of which had less than 8.5% CP. These divergent responses suggest that some forage-related factor other than potential organic matter digestibility plays some role in the need for supplemental DIP. In particular, these responses led to the suggestion that recycled N could play some role in alleviating the need for supplemental DIP. While this general response had been recognized for some time, the potential of recycled N to play a substantial role in meeting microbial requirements with low-protein forages was somewhat surprising. The potential for recycling to play a role with low quality forages was demonstrated by results of Bandyk et al. (2001). This study, which in general substantiated earlier studies in sheep by Egan (1977), showed that voluntary intake responses followed postruminal, as well as ruminal infusions of casein (Figure 4). The time delay (4 d until increase in intake with postruminal infusion vs. 1 d with ruminal infusion) and the diminished degree of intake response compared with ruminal infusion was suggestive of an effect on intake via ruminal recycling of N, though the possibility of direct stimulation of intake through improved nutrient status cannot be ruled out.

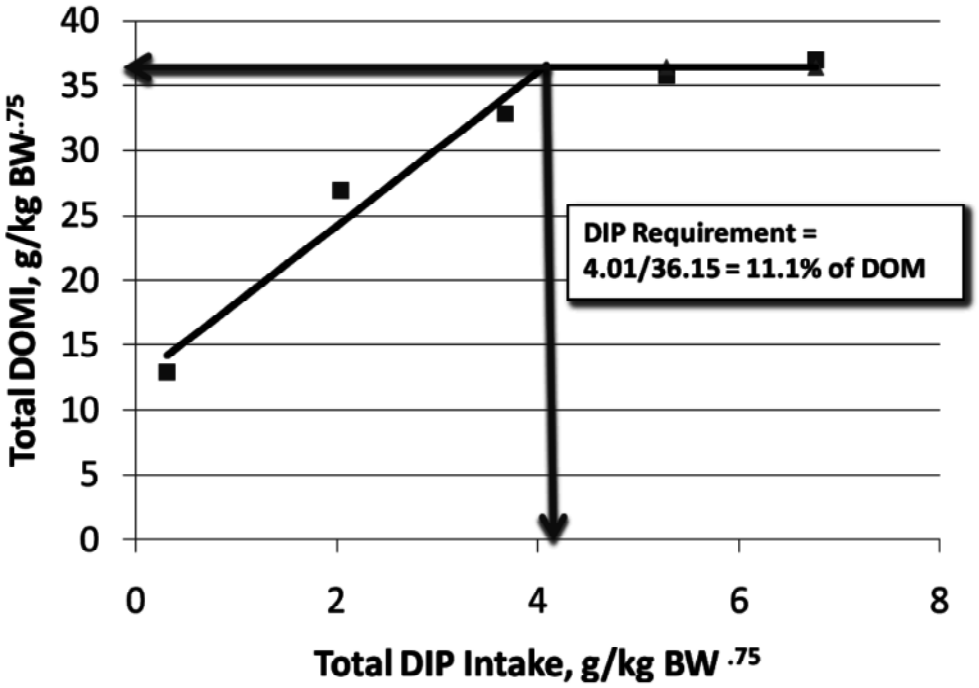

Figure 3 - Determination of degradable intake protein requirements from response in digestible organic matter intake. (Koster et al., 1996).

Thus, although the beneficial aspects of DIP supplementation with low quality forages are clear, determinations of the optimal quantity of DIP for a given forage remain elusive. Additional work is needed to clarify potential contributions of the undegraded intake protein (UIP) fraction of the forage protein to the recycled N pool. Another complicating factor when formulating supplements with DIP requirements in mind is that our goal is not always to meet the requirements, per se. In keeping with our optimization theme, it should be recognized that requirements are generally defined in order to maximize some response criterion, in this case, digestible OM intake. However, we often find that the amounts of protein supplement required to “meet the DIP requirement” can be great enough that the expense of meeting the requirement may outweigh the benefits. Thus, the

incremental responses to increasing nutrient level (i.e. the slope of the response curve before the requirement is met) are of interest.

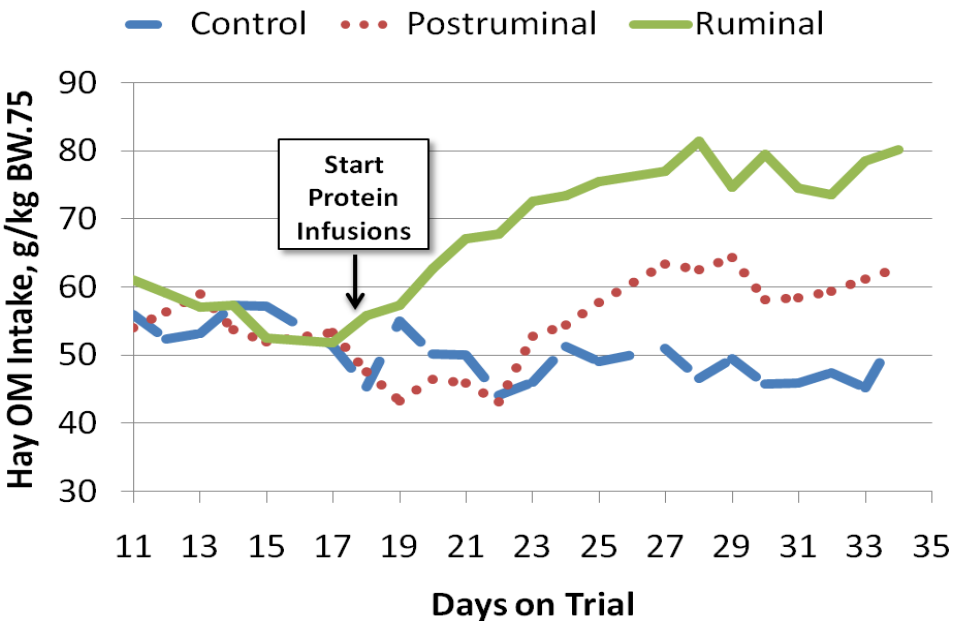

Figure 4 - Influence of ruminal and postruminal infusion of casein (400 g/d) on voluntary intake of low quality (3.4% CP; 76% NDF) warm season grass hay by beef steers. (Bandyk et al., 2001).

One way to minimize the cost of DIP supplementation is to use nonprotein nitrogen as a DIP source. Though historically, limits to the utilization of NPN with low energy diets have been recognized, more recent work has attempted to identify acceptable levels of urea to include in protein supplements. Contrary to the argument above that supplement effects on DOMI can be used to predict performance responses, there is a reasonable body of literature that indicates that urea-based supplements (when compared with natural protein supplements) can depress performance independent of effects on intake or digestibility. For example, Koster et al. (2002) found no effect of urea inclusion levels at up to 40% of the supplemental DIP on forage intake or

digestibility by steers consuming low-quality (2.4% CP; 73.5% NDF) warm season grass hay. Figure 5 shows effects of increasing the urea level in protein supplements on weight changes in one of three performance studies reported in that study. Contrary to expectations from the intake and digestibility data, cow weight changes (Figure 5) and body condition scores (data not shown) were depressed somewhat by urea inclusion levels of up to 40% of the supplemental DIP. In the experiment shown, the most dramatic negative effects were observed for supplements containing 60% of the DIP as urea, and, importantly, in one of the studies, in which cows grazing tallgrass prairie were supplemented – some failures to consume the 60% supplement were noted. Thus, urea inclusions of up to about 30% to 40% of the supplemental DIP appear to act similarly to all-natural supplements for pregnant cows. If maximal performance is not necessary, higher inclusion levels may be appropriate, given the opportunity for lowering supplement costs. However, when urea is provided in supplements to provide 50% or more of the DIP, supplement consumption may become problematic. Furthermore, there is research indicating that high levels of degradable protein consumption in and around the breeding season may interfere with reproductive performance. Thus, caution is warranted when using higher levels of NPN near the breeding season.

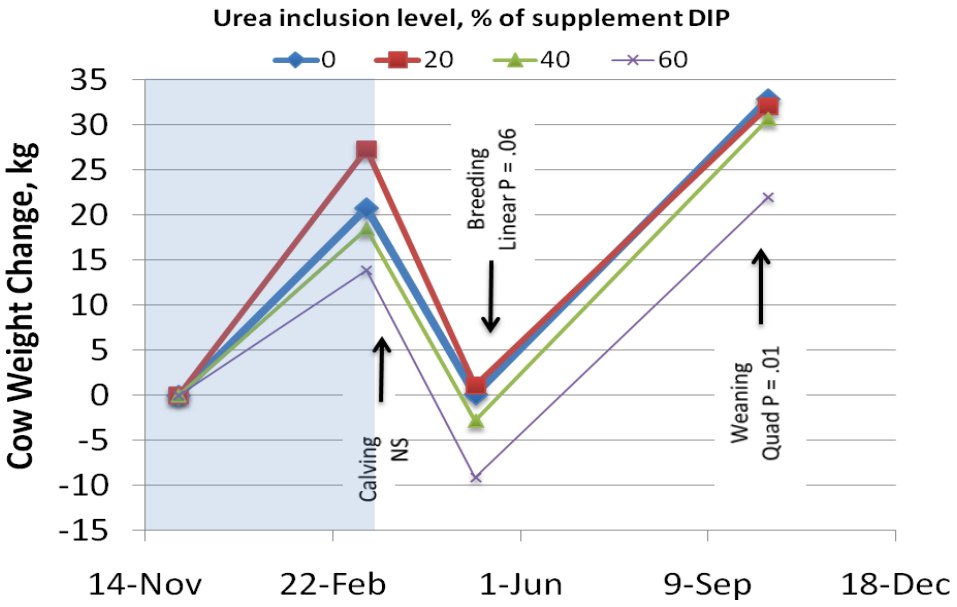

Figure 5 - Influence of increasing urea concentrations in DIP supplements on weight change of spring calving beef cows. Sorghum grain/soybean meal-based supplements were fed during the third trimester (shaded region) to spring-calving cows consuming low quality forage sorghum hay in drylot. Beginning just prior to calving, all cows were managed together as a group (Koster et al., 2002).

INTERACTIONS BETWEEN SUPPLEMENTAL DIP AND CARBOHYDRATES

Because requirements for DIP are essentially microbial requirements, and the net growth of ruminal microorganisms is set by the available energy, it follows that DIP requirements would be affected by ruminally available energy. This establishes the somewhat paradoxical situation that increasing provision of supplemental carbohydrate may increase the requirement for DIP (a possible explanation for the negative effects of increasing amounts of low protein supplements seen in Figure 2). In an attempt to quantify the nature of

the relationship between supplemental starch and the response to DIP, Olson et al. (1999) administered varying levels of starch and degradable protein (casein) to the rumens of beef steers consuming a low quality warm season grass hay. Interestingly, in that work, no interactions were observed between starch level and DIP level on DOMI – though strong linear main effects were observed for both (Figure 6). This suggests that depressions in DOMI observed with starch were independent of relationships with DIP (at least within the range of starch and DIP levels used within this study). This leads to the question of the nature of the effects of starch on DOMI. In their data, although linear depressions were observed for both digestibility (OM, $P = 0.01$; NDF, $P = 0.06$; data not shown) and forage OM intake ($P < 0.01$; data not shown), the majority of the depression in DOMI was a consequence of starch effects on forage OM intake. This suggest a somewhat different model of starch interactions with low quality forage. Typically, we have assumed that starch-induced depressions in forage intake occur subsequent to depressions in digestibility. In this work, it appears that intake depressions with starch supplementation may occur independently of digestibility depressions, and may serve to mask those changes to some degree (decreasing intake is often associated with increasing digestibility of a given feedstuff). Interactions between energy supplementation and protein supplementation have been observed, both on forage use and animal performance (Clanton, 1980; DelCurto et al., 1990). A likely reason that such interactions were not observed in the work by Olson et al. (1999) is that none of the supplements were particularly 'unbalanced' with respect to the DIP:DOM ratio. For example, they pointed out that the DIP:DOM ratio of cracked corn grain is approximately 0.049, as compared with their most extreme DIP:DOM ratio of 0.10, which is not far from the estimated "optimal" DIP ratio determined for a similar forage in the work by Koster et al. (1996).

As complicated as the story may be with starch, we have much less information regarding utilization of readily degradable carbohydrates other than starch. Typically, from a nutritional standpoint, we group all degradable carbohydrates together. However, work by Heldt (1999b) showed that, when included in supplements containing higher levels of DIP, monosaccharides may act differently than either sucrose or starch (Figure 7). In this situation, when glucose or fructose were included as the energy substrates in DIP supplements, they actually increased fiber digestion relative to starch-containing supplements. Perhaps not as

surprisingly, the effects of highly digestible fiber are also quite different from the effects of starch when included in supplements (Heldt et al., 1999a). Other work, dealing with model substrates rather than the semi-purified substrate approach used by Heldt and coworkers, has further demonstrated our lack of understanding of the metabolism of carbohydrates other than starch. Working with feedstuffs that represented high degrees of lignified fiber, non-lignified fiber, pectins, fructans, sugars or starch, Hindrichsen and coworkers found that energetic description of carbohydrates based on our current understanding was inadequate to explain differences that they found for both in vitro (Hindrichsen et al., 2004) and in vivo (Hindrichsen et al., 2006) metabolism of these feedstuffs. However, one area in which we are beginning to develop a substantial body of work is in the comparison of digestible fiber vs. starch-based supplements.

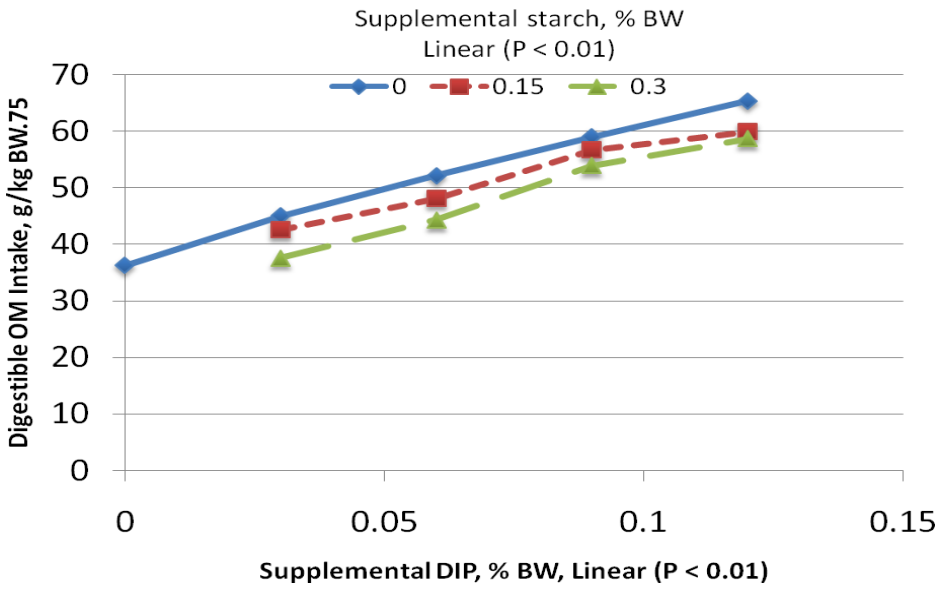

Figure 6 - Influence of ruminally infused DIP (casein) and corn starch on digestible organic matter intake by steers consuming low quality (4.9% CP, 72.3% NDF) warm season grass hay. There were no interactions (P > 0.49) between starch and DIP. (Olson et al., 1999).

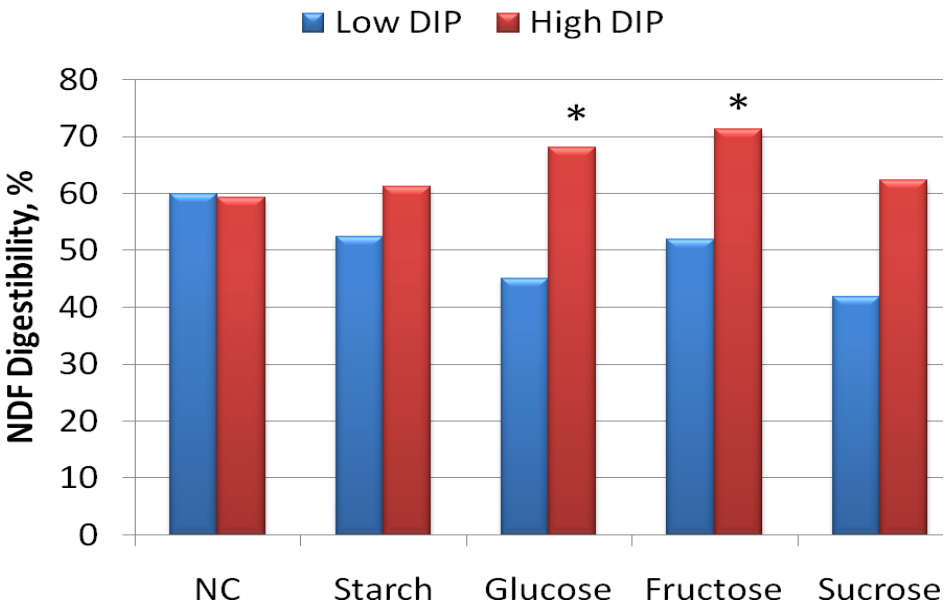

Figure 7 - Influence of starch, mono-, and disaccharides in low (.031% BW/d) and high (.122% BW/d) DIP supplements on fiber digestibility. With low DIP, carbohydrate supplementation depressed (P = 0.02) NDF digestibility relative to the unsupplemented negative control (NC) and there were no differences ($P \geq 0.21$) among carbohydrate sources. At the high level of DIP, carbohydrate supplements (containing both the carbohydrate and DIP sources) increased (P = 0.03) NDF digestibility, and differences ($P \leq 0.05$) were detected between starch and sugars and between mono- and disaccharides, but not (P = 0.36) between glucose and fructose. (Heldt et al., 1999b).

DIGESTIBLE FIBER VS. STARCH IN SUPPLEMENTS

Given the propensity of starch-based supplements to depress fiber digestion, there has been considerable interest in the use of highly digestible fibers to provide supplemental energy. Because of potential interactions between levels of DIP and the depressing effects of starch (see Figure 7, for example), it would seem that the relative comparison

between fiber- and starch-based supplements would depend upon the quality of the basal forage. We examined this concept using steers consuming various qualities of endophyte-infected tall fescue hay (ranging from 7.8 to 17.4% CP and 68.7 to 76.8% NDF) and supplemented with 0.67% BW of either corn or soybean hulls (Fieser and Vanzant, 2004). Although not precisely in the way we anticipated, the effects of supplement type did interact with forage maturity in measures of digestibility (Figure 8). Generally speaking, starch displayed a greater propensity than fiber to depress forage digestion, and these effects were more noticeable with lower quality forages. However, no interaction ($P = 0.25$) was detected for forage OM intake (Figure 9). Additionally, no difference was detectable between the two supplements in their depressive effects on intake – averaged across supplement types and forage maturities, addition of 0.67% BW supplement depressed forage intake by 0.30% BW. That fiber-based supplements are at least comparable to starch in their intake depressing effects is in keeping with much of the research literature. The differential effect of the two supplements on forage digestibility and forage intake highlights the need, in prediction models, to estimate these responses individually rather than attempting to directly predict DOMI. Recognizing that responses to supplements depend to a large degree on the quantity of supplement provided, we conducted a subsequent study (van Rensburg et al., 2003) in which we fed increasing amounts of soybean hulls (up to 1.28% of BW) to steers consuming moderate quality (14.1% CP; 68.0% NDF) tall fescue hay. A linear ($P < 0.01$) decrease in forage intake was observed with increasing level of soybean hulls (Figure 10). However, increases in total intake and digestibility combined to result in a linear ($P < .01$) increase in DOMI that amounted to a 57% improvement with the highest level of supplement compared with the unsupplemented control.

Most of these reviewed studies, from a modeling standpoint, present a rather simplified situation, in that the supplementation sources are dominated by a particular energy type (e.g. starch vs. digestible fiber). However, in practice, there are many potential feed sources that include various combinations of different carbohydrates, proteins, and lipids, each of which can interact in unique ways with each other and with the nutrients in the basal forage. We are just beginning to understand the complex relationships necessary to predict the effects of supplement composition on forage intake and utilization.

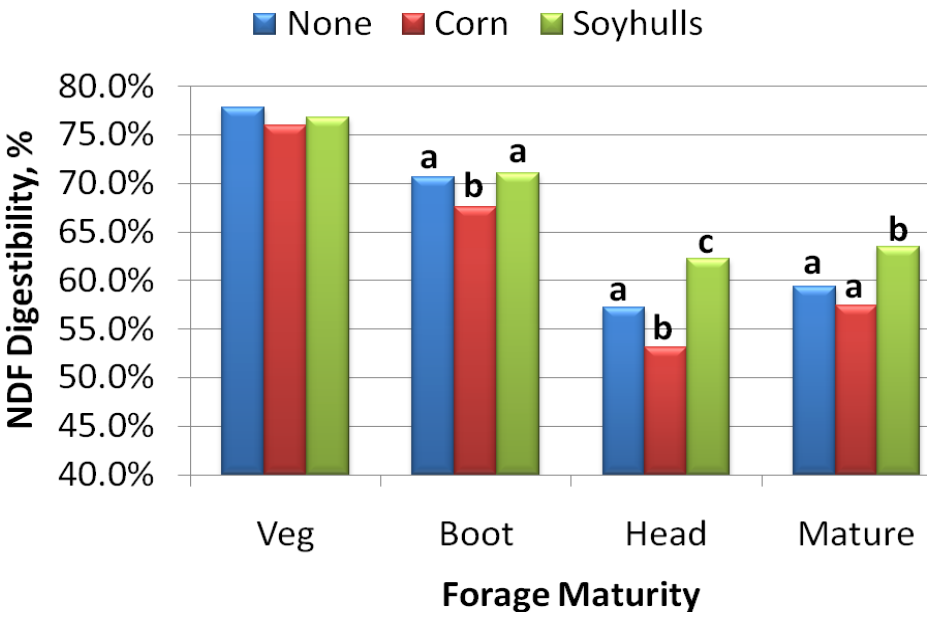

Figure 8 - Effect of supplement type and forage maturity on NDF digestibility. Supplement type x forage maturity interaction (P = 0.04). Veg = vegetative; Boot = boot stage; Head = heading stage. Means within forage type with different letters differ (P < 0.10). (Fieser and Vanzant, 2004).

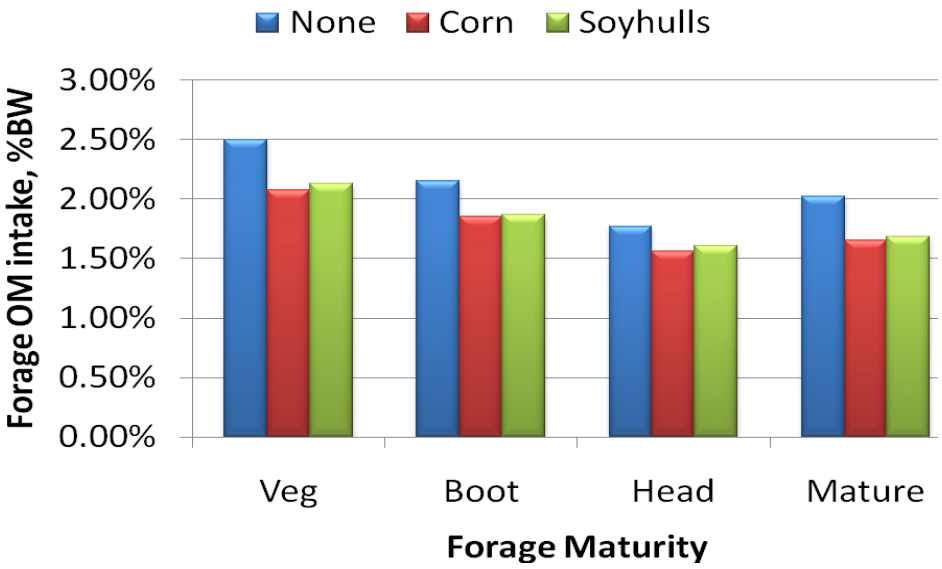

Figure 9 - Effect of supplement type and forage maturity on forage OM intake. Supplement type x forage maturity interaction (P = 0.25). Both supplements depressed forage intake (P < 0.01) relative to the unsupplemented control. Veg = vegetative; Boot = boot stage; Head = heading stage. (Fieser and Vanzant, 2004).

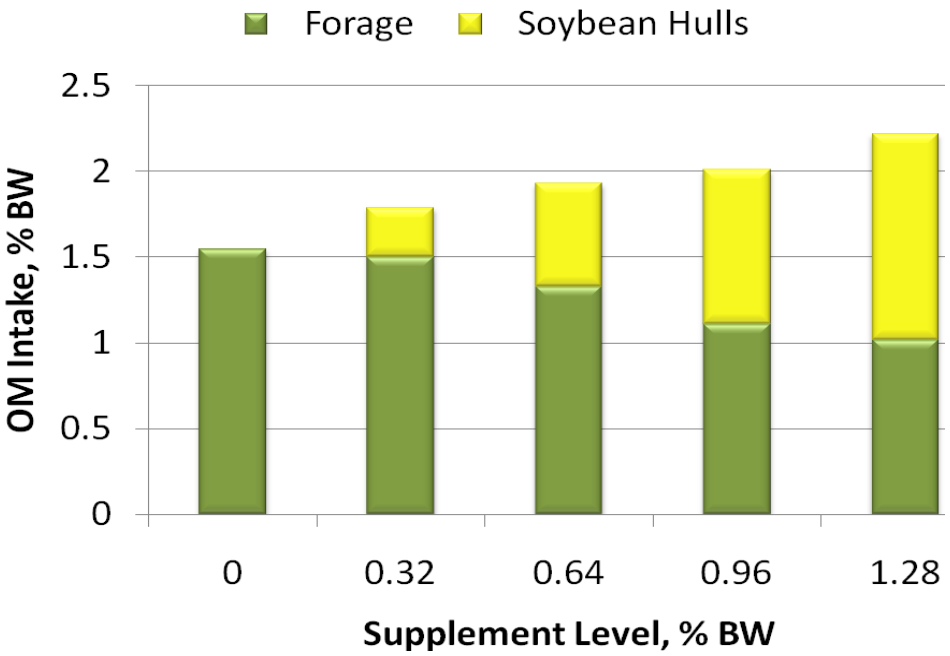

Figure 10 - Influence of increasing level of soybean hulls on organic matter intake by steers consuming moderate quality fescue hay. Linear ($P < 0.010$) decrease in forage OM intake with increasing level of supplementation. (van Rensburg et al., 2003).

ISSUES ASSOCIATED WITH TIMING

One factor that is often touted as an explanatory reason for interactions between different types of feedstuffs is asynchrony in digestion rates. Most commonly, this is discussed with respect to differences in the rate of degradation of energy and nitrogenous substrates. Theoretically, problems arising from asynchronous release of nutrients in the rumen appears logical. Some would argue, based on theoretical considerations, that, particularly with protein supplements, the degradation rates of the nitrogenous components should match the rates for the energy substrates in the basal diet. Unfortunately for the theory – the data suggest that we must establish quite severe asynchrony before any types of measureable effects can be observed.

The literature is replete with studies in which investigators have set out to detect differences due to asynchrony. In most cases, we have little to show for these pursuits. One of the most convincing pieces of evidence is a cleverly straightforward study from nearly thirty years ago. Mizwicki and coworkers (1980) used a model that was well suited to detect effects of asynchrony if they existed – steers consuming a very low quality prairie hay (2.6% CP; 52.9% ADF) with a modest amount (606 g/d) of corn-based energy supplement were provided with supplemental urea on a continuous (3.5 g urea/h for 24 h), moderate (14.2 g urea/h for 6 h), or rapid (85 g urea in 1 h) basis. Ruminal NH_3 N concentrations responded as would be expected with such a high degree of asynchrony between N and energy availability in the rumen (Figure 11). However, although they obtained responses to urea per se, there were no effects of administration rate on measures of digestibility (data not shown) or N retention (Figure 12). The authors' explanation for the lack of effects of asynchrony is as logical today as it was then – urea recycling has tremendous potential to compensate for rapid release rates of NH_3. Thus, it should not be surprising that (at least two of three) papers generated from a sponsored symposium on "synchrony" at last years' annual ASAS meetings (Cole and Todd, 2007; Hall and Huntington, 2007; Hersom, 2007) determined that, although sound in theory, there's little evidence to support adverse effects of asynchrony

Before we abandon the possibility of asynchrony-generated nutrient mismatches – we should consider whether there are even more extreme situations than that tested by Mizwicki et al. that deserve consideration. With grazing animals, the opportunity exists, and is often exploited, to provide supplements on a less-frequent-than-daily basis. In addition to providing insights into practical management strategies (ways to optimize the supplementation system), a brief look at this area of research can provide some additional insight into the concept of synchronous nutrient supply. Since the mid-1990s there have been quite a few publications evaluating frequency of supplementation issues. Generally, these papers (Bohnert et al., 2002; Currier et al., 2004; Farmer et al., 2001; Huston et al., 1999) support the notion that, although more frequent supplementation often yields greater intake and/or digestibility responses in confinement studies, protein supplements can be offered as infrequently as once weekly with minimal effects on animal performance. This is reasonably good evidence that synchrony is overrated. However, a couple of finer details are worthy of

investigation. Although nitrogen recycling can account for the failure of excessive rates of N release to become mismatched with energy release rates, there is still a question of whether too rapid a supply of energy release could prove disadvantageous. More specifically, though we can feed protein supplements as infrequently as once weekly, what if I were to try the same with a starch-based energy supplement? To test this, Beaty et al. (1994) fed 4 different supplements either daily or 3 times weekly to beef cows grazing winter range in the tallgrass prairie. The four supplements contained varying proportions of crude protein (ranging from 12% to 41%). In this situation, with very low forage protein concentrations, one might anticipate that infrequent supplementation of a low protein supplement would prove catastrophic. In fact, no interactions ($P > 0.10$) were found between supplement type and frequency of supplementation. Further, although positive responses in cow weight and body condition score changes and calf ADG were observed with increasing supplemental protein concentration, frequency of supplementation was essentially without effect. Another situation in which we might expect a particularly bad outcome with infrequent supplementation is the scenario in which high levels of NPN are included in the supplement. This was tested by Farmer et al. (2004) who did find that less frequent supplementation could be disadvantageous when feeding high levels of urea, which they defined as levels that supplied greater than 30% of the DIP as urea. However, most of the disadvantage was related to the fact that with infrequent offerings of these high urea supplements, they had a high rate of supplement refusal. Thus, even in some of the most extreme circumstances evaluated (low protein supplements on poor quality forage diets, supplementing as infrequently as every 3 d, high levels of rapidly degraded urea in supplements) there is little evidence that synchrony of nutrient release is a relevant issue. From a practical standpoint, it appears that supplements can be offered less frequently than daily without sacrificing much in the way of animal performance, provided that supplement consumption does not become an issue.

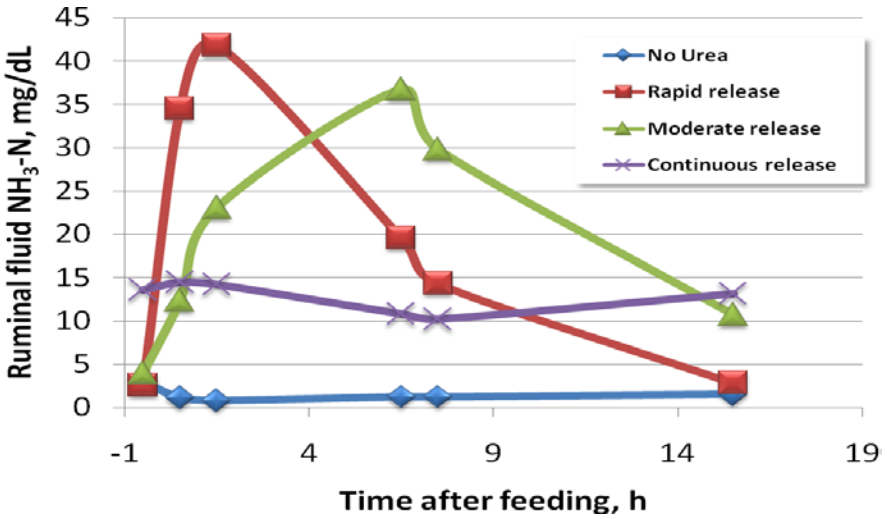

Figure 11 - Influence of urea administration rate on ruminal ammonia N concentrations in steers fed very low quality prairie hay. (Mizwicki et al., 1980).

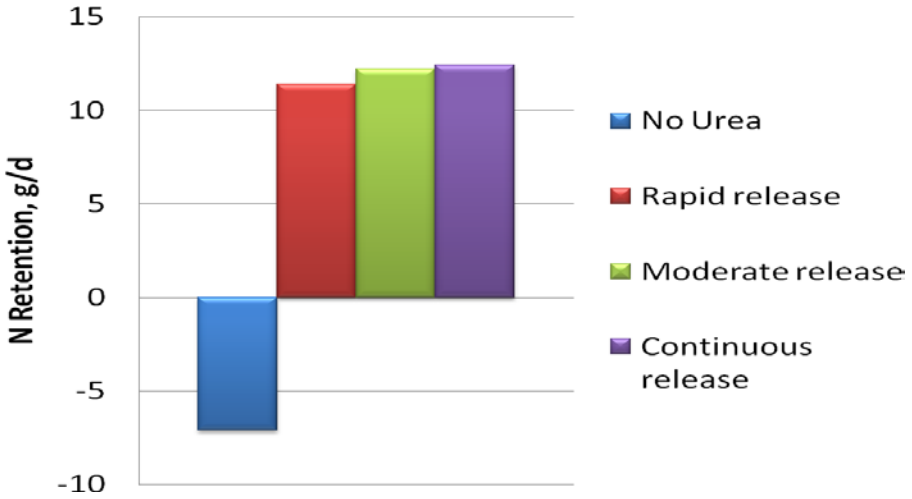

Figure 12 - Influence of rate of urea administration on N retention in steers consuming a very low quality prairie hay. Urea vs. no urea ($P < 0.01$). (Mizwicki et al., 1980).

PUTTING THE PIECES TOGETHER

The preceding discussion shows that in many ways we have not advanced tremendously from the empirical, discrete classification system portrayed in Boussingault's 1845 publication. We still, to a large extent, deal with feedstuffs as discrete entities and continue on our quest to measure every possible combination and permutation of supplement with forage. Are we ever to move beyond this approach toward a more comprehensive, generalized, understandable system? Thanks to the tedious, visionary work of a few individuals, I believe we are on the path toward this system. However, to make meaningful progress toward this end, we each have a role to play. To illustrate, let us consider the models presented by Moore et al. (1999). Moore constructed regression models based on literature data to determine effects of supplementation on forage intake, and total diet TDN. These models were developed with recognition that supplements interact with the basal forage such that forage intake may be either increased or decreased with supplementation, and total diet TDN may be greater than or less than predicted by an additive model (through positive or negative associative effects on digestibility). It should be recognized that, in order to predict a change in response to supplementation, one must first have data relating to the unsupplemented diet: specifically, data from unsupplemented, negative control treatments is necessary to apply this approach. In fact, voluntary forage intake without supplement is a key independent variable in the Moore et al. (1999) equation for prediction of forage intake with supplement , presumably as an important measure of overall forage quality. This is important not only for those who wish to apply Moore's model – it is important for those conducting supplementation research. If we are to continue to elaborate predictive models, we need to ensure that our studies contain the requisite material necessary for model development. The presence of a negative control is one of those necessities. Other necessities include adequate chemical description of the dietary components, as well as of the animals under investigation. Too much work and expense goes into research projects to have their ultimate utility compromised because of insufficient reporting of potentially salient data.

The Moore et al. (1999) equations are but one approach, and are but a beginning. For example, using data from Fieser and Vanzant (2004), we used the Moore et al. (1999) model to calculate the estimated

change in forage intake and total diet TDN (roughly equivalent to OMD). Comparing these estimates to the observed responses, we found that, with corn, the model predicted, on average, a 0.2% BW greater depression in forage intake than was observed in this study. With soybean hulls, the model overestimated the depression in forage intake by an average of only 0.1% BW. Because the TDN-prediction model contained no terms for supplement composition, similar negative associative effects were predicted for the two supplement types (-4.2 and -4.0 percentage units deviation from an additive model for corn and soybean hulls, respectively). The model did a reasonable job of predicting the observed associative effects with corn (-5.9 percentage units), but over predicted the observed response with soybean hulls (0.3 percentage units). These results are not surprising, given the available data with which the model was constructed. Very few reports containing digestible fiber supplements were available. Researchers conducting work in this area should take care to make themselves familiar with the existing modeling efforts, and include all data that would be relevant for incorporating their work into models that will ultimately obviate the need for evaluating all possible combinations of supplements and forages.

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OPTIMIZATION OF FEEDLOT DIETS WITH HIGH DENSITY OF ENERGY AND NUTRIENTS

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Feedlot cattle in the US typically are fed diets rich in grain (maize, sorghum grain, barley, and grain byproducts) supplemented with protein (oilseed meals and urea), vitamins, and minerals. Diets rich in energy and nutrients are preferred for several reasons. First, when compared with grazed or harvested forages, concentrate diets usually provide net energy for gain (NEg) at a lower cost. Second, rate of weight gain is greater with concentrate- than roughage-based diets; this reduces the time period that cattle are fed, and a shorter feeding period reduces the cost of interest on the capital invested in animals. Third, compared with grazed forages, the energy expended for maintenance is lower for cattle confined to feedlot pens, and for cattle in feedlot pens, high concentrate diets are more readily transported, handled, and processed and result in less indigestible waste than forage-based diets. Finally, the worldwide desire for marbled beef is most readily achieved at lower carcass weights by feeding high concentrate diets. Because the fixed cost for grain processing equipment is high, such equipment is suited best for large feeding operations. Large operations obtain economic advantages of scale associated with investments in specialized equipment (for feed and animal procurement, feed and animal transport and processing, and feed delivery) and specialized personnel (cattle management specialists, nutritionists, veterinarians, purchase and sales agents, accountants). The recent surge in competition from ethanol plants for grain has markedly increased the price of energy and of grains as well as the amount of ethanol byproducts being included in feedlot diets. After most the starch has been removed, wet and dry distillers' grains are rich in oil and digestible fiber. Today, feedlot gain is least costly in geographic regions where wet distillers' grains will comprise up to 40% of the diet, fully displacing protein supplements and a portion of the dietary grain. Despite their small particle size and higher fiber content, distillers' grains can handled and fed like concentrates but are less likely than grain to cause acidosis due to their low starch content. Nutritional value of distillers' products

appears greater when combined with dry rolled and high moisture than with steam flaked maize (Vander Pol et al., 2006) though specific reasons for this difference remain unclear. Nevertheless, higher grain prices will increase the value of processing grain extensively. When combined with availability of low cost ethanol byproducts, this has forced feedlot nutritionists to re-evaluate their diets and re-formulate diets to attain least cost gains, not just least cost diets. This paper will describe some of the goals and limitations of feeding high concentrate diets to finishing beef cattle. Typical concentrations of the major dietary components fed in US feedlots as reported from a survey of feedlot consulting nutritionists (Vasconcelos and Galyean, 2007) will be highlighted and implications for cattle feedlots in Brazil will be discussed.

FORAGE (ROUGHAGE) SOURCES AND CONCENTRATIONS

According to that 2007 survey, roughage is being fed at an average of 8.5% (summer) to 9% (winter) of diet dry matter with an overall range of 0 to 13.5% in US feedlots. The most prevalent roughage sources are maize silage, alfalfa (chopped hay or silage), and sorghum silage; cottonseed hulls, cotton burrs, and sudangrass hay occasionally are fed. Crude fiber and NDF are methods by which feedlot nutritionists quantify and contrast quality and value and substitute forages.

Traditionally, feedlot diets have been formulated with only enough forage (harvested whole plants) or roughage (a term that includes both forages and fibrous by-products of industrial processing) to dilute both the ration and ruminal contents and to stimulate saliva flow (during eating and rumination) to reduce the incidence of acidosis. The amount of roughage that is fed represents a compromise between the benefits noted with feeding high roughage levels (increased ruminal pH and dry matter intake and reduced liver abscess incidence) versus the advantages noted with feeding low roughage levels (often a lower cost of NEg, a high dietary NEg concentration that decreases the amount of feed to be handled and delivered, an increased ruminal propionate concentration that reduces methane loss, an increased carcass dressing percentage, and a decreased heat increment of the diet.) In limited cases, roughage will be totally removed from the diet if the diet contains either a very coarse or whole maize grain (that stimulates chewing and rumination) or a very high amounts of feeds and byproducts (e.g.,

distillers' grains) that are low in starch. The ideal dietary concentration of dietary roughage can differ with source of roughage, grain processing, and the specific response criterion chosen (Figure 1).

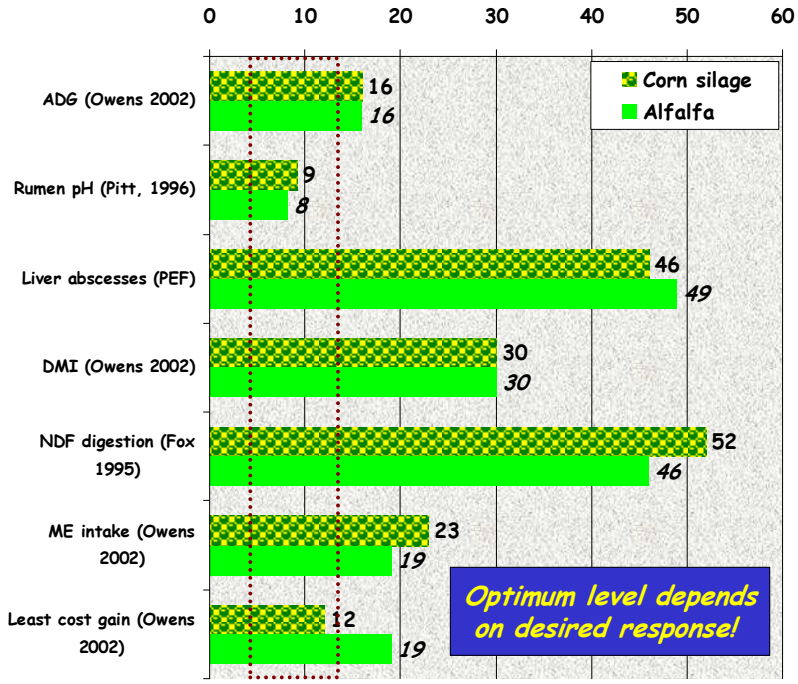

Figure 1 - Dietary roughage levels where various responses were maximized based on $3.20/bushel maize, $125/ton alfalfa, and $31/ton maize silage at 33% DM.

Note that extremely high roughage levels of these two forages are needed to maximize dry matter intake and NDF digestion and to avoid liver abscesses. To maximize intake of metabolizable energy and rate of weight gain, lower dietary levels of maize silage and alfalfa can be fed, but the optimum levels still are greater than that the 9% level fed at most feedlots based on the prices used for calculating costs in Figure 1. In addition, the ideal feeding level will change as relative costs of roughage and grain change; higher roughage concentrations become more desirable when grain prices are high and roughage prices are low. Because alfalfa and maize silage will increase intake of NEg and rate of

gain, formulating diets on the basis of least cost per unit weight of the diet or unit of dietary NEg often does not yield the least costly weight gains. Source and level of roughage can alter site and extent of starch digestion.

Forages and roughages differ in bulkiness and fiber (NDF) content, particle size, and composition (cellulose, hemicellulose, lignin) as shown in Figure 2.

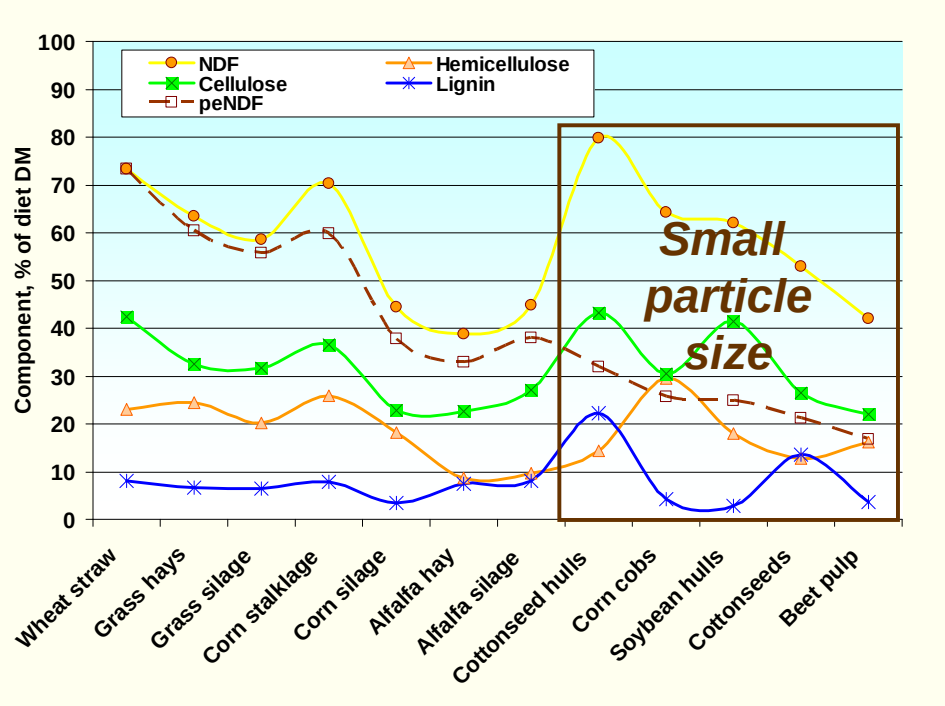

Figure 2 - Concentrations of NDF, its components, and "physically effective" in common forages and roughages.

Feed formulators consider three primary factors when selecting among various sources of dietary roughage. First comes roughage availability and its final cost relative to its nutritive value in the diet, second is its "roughage" value, and third is its capacity to mix with other diet components and reduce particle segregation.

Because most roughage sources have a low bulk density, they are costly to transport. Consequently, locally available forage sources

usually are preferred. Long forages are chopped to simplify handling and mixing and avoid separation and sorting, but the cost of and equipment for grinding and persistent problems with forage dust (personnel, equipment, and the dust and fire hazards) must be considered. Silages typically are processed at harvest; this simplifies feeding, but the whole grain in mature silages often is not well digested. Kernel processing at harvest increases the digestibility of starch from more mature maize silage and probably for sorghum silage, as well. Protein and minerals supplied by legume forages will reduce the need for and cost of protein supplements in the diet.

Though NEg supplied by the forage is of major interest to dairy cattle nutritionists, NDF is not well digested by cattle fed high concentrate diets. Thereby, wise feedlot nutritionists will consider dietary forage more as a diet component that dilutes the diet rather than a source of NEg for cattle. Indeed, the NEg of roughages in feedlot diets probably is grossly overestimated. This is because tabular NEg values for roughages typically are based directly on total digestible nutrient (TDN) content of the forage when it is fed alone at low levels of intake, not at high intake levels as part of a high concentrate diets. Because NDF digestibility of forage is depressed when fed with concentrates, the tabular estimate for NEg of forages in feedlot diets likely is overestimated. Conversely, this means that NEg values for the grain portion of the diet will be underestimated simply because the NEg contribution from roughage in the diet to NEg of the total diet was overestimated. Indeed, in several feeding trials, efficiency of gain has been superior for feedlot diets that contained wheat straw than for similar diets that contained chopped alfalfa hay! Hence, “quality” of forages evaluated by procedures applicable for high roughage, dairy type diets are not applicable when forages are fed at low levels in high concentrate diets. Certainly, feedlots need not compete with dairy producers for the premium quality, low NDF, more costly forages. For deriving realistic NEg values for individual forages and roughages included in feedlot diets, diet NDF digestibility of feedlot rations should be monitored or performance-generated NEg values should be curvilinear regressed against various dietary forage concentrations.

“Quality” of dietary forage, as measured by acceptability and digestibility (often high protein and low NDF) still is critical when high amounts of forage are included in the diet and when feedlot calves are being adapted gradually, typically during a 3 to 4 week transition period,

to high concentrate diets. During adaptation, the ideal forage will mimic the forage that previously had been grazed or fed. For starting cattle, fermented forages often are avoided because such cattle usually are not familiar with and thereby may not readily consume silages.

The performance benefits from higher dietary concentrations of forages than commonly fed noted in Figure 1 probably reflect actions of forage above and beyond the NEg being supplied, e.g., reductions in animal health problems and in the incidence of sub-clincal acidosis, or a shift in site of starch digestion from the rumen toward the intestines. Though most feedlot consultants still evaluate roughage sources on the basis of crude fiber, the scale for "roughage" value of forage used by most dairy nutritionists is its "physically effective" fiber (PEF) content (Figure 2). Based on particle size and NDF content, PEF is an attempt to quantify the ability of roughage or forage to stimulate chewing and rumination; hence, roughages with small particle size provide less PEF. Exchange and substitution among sources of forage in feedlot diets should be based on NDF or PEF content of the forage. This means that when dietary forage A replaces forage (B) that contains twice as much NDF, twice as much of forage A must be included in the diet.

For handling and mixing with other diet components and avoid separation of diet components in a mixer or in the feed bunk, long stem forages typically are chopped or ground even though grinding reduces PEF. To avoid pulverizing the dry leaves of roughages, particularly with legumes, some feedlots use hay slicers rather than large tub or stationary grinders to grind forages. Roughages differ in their ability to reduce segregation by cattle and avoid separation of fine grain particles the diet. The high prevalence of silages in feedlot diets (being the first or second roughage source used by 75% of feedlot nutritionists) probably reflects the capability of moist feeds to trap small grain particles that otherwise could separate from other diet components. When moist forages are not convenient for feeding, other products (molasses, fat, water) often are added to the diet to reduce separation of fine particles. Fine particles that are rich in starch represent a feeding hazard. With rolled and ground grains, fines are primarily floury starch particles whereas with steam rolled and steam flaked maize grains, fine particles, being partly derived from the germ, usually contain more oil and less starch. When timid cattle or groups are forced to "clean the bunk" and consume large amounts of fine particles or cattle sort and select diet

components that are rich in starch, they often suffer from clinical or sub-clincal acidosis due to rapid ruminal fermentation of fine grain particles.
Implications. Until more precise estimates of NEg of forages and grains become available, feedlot consultants worldwide would be wise to formulate diets on the basis of least cost of diet NEg but maintain some minimal dietary NDF or PEF concentration specific for the grain source and processing method employed. Choice among forages logically should be based on PEF of the forage, roughage availability, capacity for handling, storing, and feeding, and its potential to prevent segregation of ration components before or after delivery of feed to the cattle.

GRAIN SOURCES AND PROCESSING

The primary grain fed in US feedlots is maize grain (Vasconcelos and Galyean, 2007). Within North America, maize implies dent yellow grain (USDA #2 yellow grade); starch of dent maize grain produced in the US will range from 45 to 65% vitreous (hard) starch at maturity, being far less vitreous than the flint maize grain hybrids frequently fed in many other parts of the world. The secondary grains fed at feedlots included wheat, sorghum, and barley. Prevalence of grain forms and grain levels reported by US consultants are presented in Figure 3.

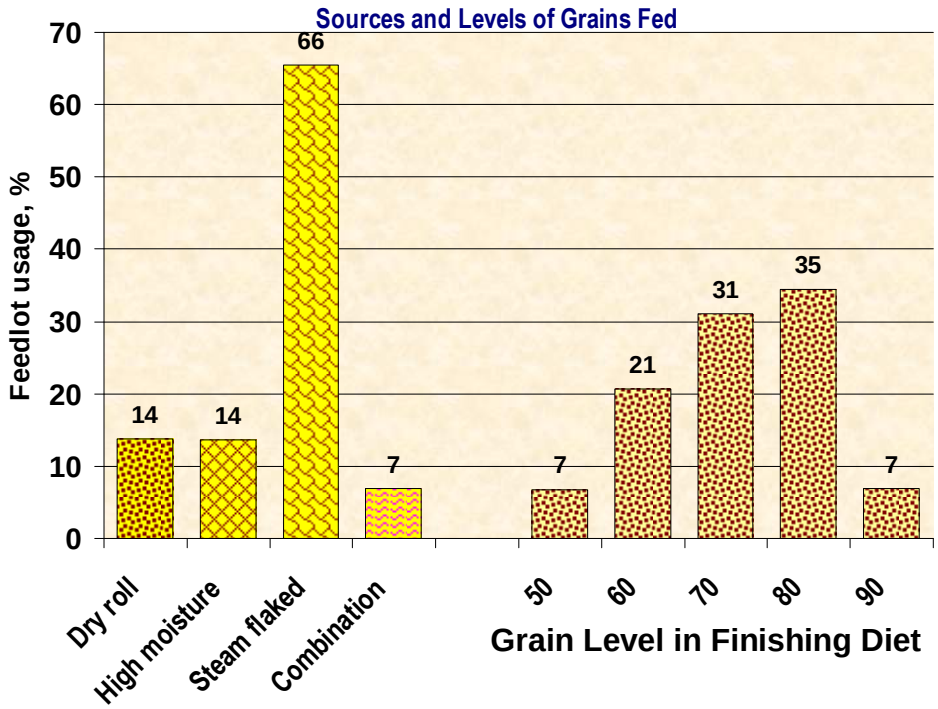

Figure 3 - Sources and levels of grains fed in US feedlots (Vasconcelos and Galyean, 2007).

Why is grain for livestock processed? To enhance its nutritional value, primarily through increasing starch digestibility. Feeding value is a function of three factors: nutrient content, intake, and digestibility. Physical and chemical characteristics of a grain will alter its digestibility, its dustiness and acceptability (palatability), and its associative effects (interaction with roughage within the digestive tract). Though tradition plays a role in grain processing, the ideal processing method should be selected based on its ability to enhance starch and dry matter digestibility and diet acceptability without detrimentally affecting ruminal pH and causing digestive dysfunction. Because the primary source of NEg available from cereal grains is starch, digestibility of starch has been the primary factor used to monitor response to processing. However, factors beyond digestibility (site of digestion; methane loss; associative effects) can be altered by grain processing; performance-

based NE values provide a more reliable and complete index of the full responses to grain processing than total tract digestibility alone.

Digestibility and performance responses to grain processing by ruminants have been reviewed extensively (Nocek and Tamminga, 1991; Huntington, 1997; Theurer et al., 1999a; Rowe et al., 1999; Firkins et al., 2001; Harmon and McLeod, 2001, 2005; Owens and Zinn, 2005, 2008). For detailed comments about the impact of site of digestion on energetic efficiency and differences among hybrids and maize types on digestibility, readers should examine other reviews (Owens and Zinn, 2005; Harmon and McLeod, 2005).

All grain processing methods involve reduction in particle size with or without addition of water and heat. Grinding or rolling dry or wetted grains to form dry rolled or dry ground grain is the most common method for grain processing. For more extensive processing, grain can be rolled or ground and, when packed into storage, it will ferment if adequate moisture (typically 24 to 35%) is present or added. Moisture may either be inherent in the grain due to early harvest forming high moisture grain or added to dry grain to form reconstituted grain. Grain reconstitution is not practiced in the US probably due to the increased labor as well as needs for storage time and facilities and the potential for energy loss during fermentation. Yet, results of feeding trials indicate that reconstitution process markedly improves starch digestion. To form steam rolled or "flaked" grain, dry whole grain is moistened with steam and crushed between corrugated rolls. Compared with steam flaked grain, steam rolled grain is steamed for a shorter time, crushed flakes are thicker, and starch is less gelatinized (damaged). Gelatinized starch is fermented or digested very rapidly. Steam rolling or flaking requires extensive equipment and high energy costs for steam generation, but starch digestibility of well processed flaked dent maize and sorghum grain approaches 100%. Effects of processing on site and extent of digestion will vary with processing conditions (grain moisture, screen size or roll gap; fermentation moisture and time; steaming time) as discussed by Zinn et al. (2002). For less extensively processed maize, feeding value can vary with the hybrid or variety of the grain and agronomic conditions, but steam flaking and fermentation will equalize the value of a grain from various sources. The more vitreous the grain, the greater the increase in starch digestibility attained from extensive grain processing. Though direct comparisons are not yet available for all processing methods, response to extensive processing should be

greater with flint than with dent maize grain because the starting point in starch digestibility is lower. Finally, chewing and rumination as well as bunk management can alter site and extent of digestion and passage rate through the digestive tract; these vary with animal age and background, diet composition, feeding frequency, and dietary forage or fiber (NDF) level. Characteristics of grain processed by various methods are highlighted below.

Dry rolled maize and whole maize. As noted in classic studies from Beltsville (Moe and Tyrrell, 1976), dry maize grain should be ground finely to maximize total tract starch digestion. Benefits from fine grinding are greater for grains that have a more of their starch in the vitreous form. Certainly, particles that are large and resist uptake of water also resist attack by microbes in the rumen and enzymes in the intestines. Though fine grinding can enhance extent of starch digestion, primarily due to enhanced starch disappearance in the rumen, starch from rolled maize or sorghum grain that escapes ruminal digestion is poorly digested in the small intestine; instead it is partially and inefficiently fermented in the large intestine. Baker and Herrman (2002) describe how sieves and shakers are used to appraise the particle size of ground grain. When sufficient roughage is present in the diet to prevent acidosis and when cattle are frequently fed a totally mixed ration, grinding to a fine particle size is unlikely to cause acidosis but can improve starch digestibility and feed efficiency. Grain can be either rolled or ground to reduce mean particle size. Compared to rolled grain, ground grain typically has a much larger range in particle size because more fine particles are generated by impact forces than by crushing forces. Hence, GMD alone, though useful, is incomplete as an index of processing. Baker and Herrman (2002) describe additional components (particle surface area; particles per gram) that can be calculated through sieving processed grain. Presence of fines and GMD also will vary with moisture content and vitreousness of the grain being processed; wetter and more vitreous dried grains generate fewer fine particles so that processed grain will have a larger GMD. With whole maize grain, less than one-third of starch entering the abomasum disappeared post-ruminally! This matches field observations that a diet composed of whole shelled maize is well used by feedlot cattle only when roughage levels are very low (under 10%); this low roughage level permits grain to be retained in the rumen to be ruminated and fermented; with such a

diet, feed efficiency occasionally is better for whole maize diets than for rolled maize diets. Adding roughage to the diet shortens the time period that particles are retained in the rumen for fermentation. Extent to which roughage particles separate from grain within the rumen also appears important; separated grain that settles in the rumen is not ruminated and large maize fragments are not well digested either in the rumen or post-ruminally. Indeed, ruminal outflow rates for starch greater than 20% per hour have been reported for high producing lactating cows (Ying and Allen, 2005). Such rapid outflow, being as fast as for ruminal liquids, indicates that some of the consumed starch is flushed from the rumen rapidly, possibly being sluiced through the rumen, instead of mixing fully with ruminal contents and retained for digestion. Such rapid passage is more prevalent with very dense grain particles if 1) the rumen is stuffed with fiber, 2) feed intakes are high, and 3) grain is fed or consumed separately from forage.

High moisture maize. Three factors are critical for obtaining maximum feed efficiency and ruminal starch digestion from high moisture maize grain -- adequate moisture content (preferably above 26% moisture), grinding or rolling of the grain, and a sufficient duration of fermentation. For some unknown reason(s), when maize is harvested and ensiled at a mid-moisture range (between 20 and 24% moisture), such grain results in poorer feed efficiency than either drier (rolled) grain or wetter grain. Moisture level and storage time responses have been reviewed previously (Owens et al., 1986; 1997) and demonstrated both in vivo (Jaeger et al., 2004) and in situ (Benton et al., 2004). Results from the latter trial indicate that when high moisture maize contains over 28% moisture, in situ disappearance of starch in the rumen will increases rapidly during the first month of storage and this increase continues steadily for at least nine months! This increase in starch disappearance parallels the increase in N solubility seen with longer storage times for high moisture maize grain. Applying this principle, wetter high moisture maize, typically harvested first, should be fed first whereas drier high moisture maize, harvested last, should have water added and be allowed to ferment for a longer time period. This is precisely the opposite the first-in last-out system used at most feedlots and dairies that are equipped with upright or bunker silos! Furthermore, an increased rate of ruminal fermentation of high moisture grain stored for many months can place cattle fed fermented grain stored longer at

greater risk of acidosis. Because maize grain that is reconstituted (water added and allowed to ferment) yields similar in situ starch disappearance and feed efficiency values as maize grain harvested at a high moisture content, the greater digestibility of starch from high moisture than dry rolled grain appears to be due largely to the fermentation process, not to immaturity of grain kernels harvested at a high moisture content. Because increased starch digestibility with a longer storage time is correlated with solubilization of maize proteins that encase or link starch granules, the type and activity of bacteria inherently present on the crop or added to harvested grain as an inoculum likely will influence starch digestibility.

Steam flaked maize. As thoroughly reviewed by Zinn et al. (2002), the degree of damage of starch and extent of denaturation of protein within flaked grain varies with processing conditions. Flake thickness and density (bushel weight of flakes) are used as quality control indices at the flaker. Starch availability (glucose release during exposure to amylolytic enzymes or gas production when incubated with yeast) is the most common laboratory method for monitoring flake quality; unfortunately, lab results usually are obtained only long after the grain is fed. The relationship of bushel weight of maize grain (from dry rolled grain all the way to grain that has been steam flaked at various densities) to total tract starch digestibility is illustrated in Figure 4. Starch disappearance in the rumen and of starch that reaches the small intestine consistently is greater for flakes that are thinner and have a lower bulk density (Owens and Zinn, 2005).

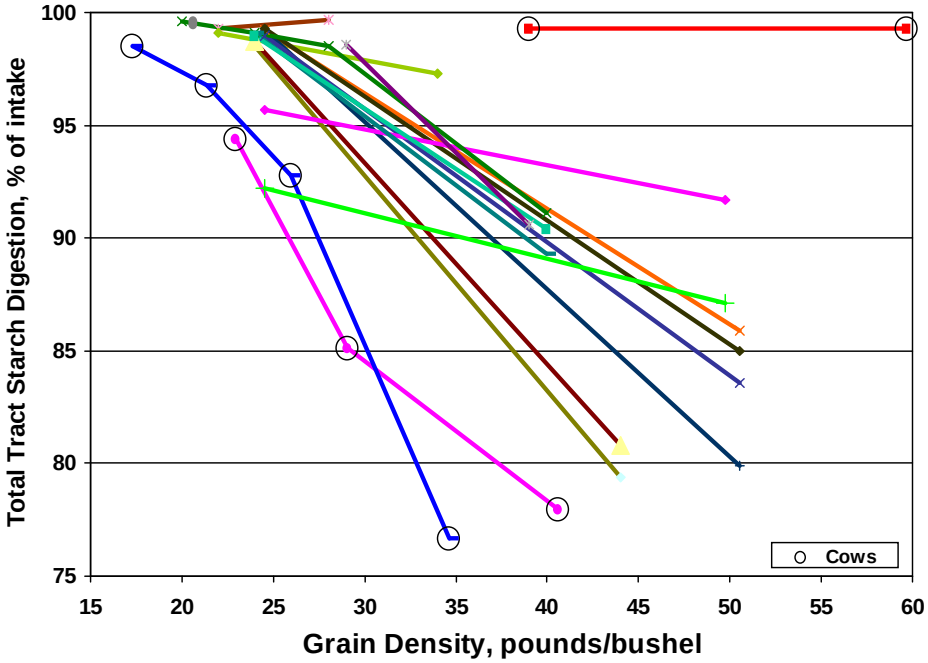

Figure 4 - Influence of density of processed grain on total tract starch digestion. Each line presents values from a single experiment and lines connect individual diets within the experiment.

Based on Figure 4, total tract starch digestion by feedlot cattle generally exceeds 98% whenever flake density equals or is less than about 30 pounds per bushel. Surprisingly, the feedlot consultant survey results indicate that feedlots currently have 27 pounds per bushel as their density target with a range of only 24 to 28 pounds per bushel (Vasconcelos and Galyean, 2007). Maize flaked to a very light test weight often depresses feed intake by feedlot cattle, possibly due to greater gelatinization and elevated ruminal acid concentrations. Consequently, processing for maximum starch digestibility through gelatinizing more than 50% of the starch to further increase digestibility is not desirable unless grain cost is sufficiently high to justify some sacrifice in rate of gain or the diet is diluted with feeds with low starch content (e.g., distillers' byproducts). These two factors, very high grain

prices and increased availability of ethanol byproducts, probably are responsible for the low bushel weight targets currently being used. If abomasal starch from flaked grain can be digested in the small intestine, and if absorbed glucose is used more efficiently than absorbed volatile fatty acids, the optimum energetic efficiency may be reached at a slightly higher flake weight than needed to obtain a total tract starch digestibility of 100%. Zinn (1990b) demonstrated that within a processing system, total tract starch digestion increased as flake density decreased; NEg of steam-flaked maize was greatest when total tract starch digestion was approximately 99%. For a given mill (flaking system), he suggested that flake density should be adjusted to achieve 99% starch digestion (typically less than 4% starch in fecal dry matter when additional starch is not provided by other diet components like maize silage). Specific grain components that limit cereal grain digestion and their response to grain processing were outlined by Rowe et al. (1999).

Grain vitreousness. One of these factors of specific interest with flint maize grain is vitreousness of the starch of the kernel endosperm. Yellow dent maize grain as well as sorghum kernels have from 45 to 65% of the starch is present in the horny (hard or vitreous) endosperm where starch granules are densely packed within a protein matrix. The remaining starch as well as the starch present in other grains (barley, oats, wheat) is deposited largely as floury starch. Vitreousness or the horny to floury (H:F) ratio can be estimated through physical dissection of kernels, by measuring absolute density (not simply test weight) of the grain, or by grinding with a Stenvert mill. The H:F ratio varies genetically, being greater for maize grain classified as flint (versus dent) grain. This ratio often increases with grain maturation and nitrogen fertility (that also increases crude protein content of maize grain). When isolated from barley, maize, and sorghum grain, starch granules have digestion rates all are equal, presumably because those granules come primarily from floury starch or because the protein matrix is altered. In contrast, several workers have reported that when incubated in the rumen within Dacron bags (in situ), starch loss from ground maize grain is slower for hybrids that have a high H/F ratio (Phillippeau and Michalet-Doreau, 1997; Phillippeau et al, 1999; Shaver and Majee, 2002). Close examination of Dacron bag disappearance curves reveals that almost all of the increased loss of starch from floury hybrids occurs before fermentation begins (wash loss). Certainly, floury hybrids generate more

fines during grinding, and fine particles will readily sift through pores in Dacron bags even without being digested. The advantage of having more particles that are very fine that can be flushed with liquid through the rumen is debatable. Increased total tract digestibility from finer particles should be beneficial, and post-ruminal starch supply will increase if fine particles are flushed rapidly through the rumen. However, if retained in the rumen, fine particles from the floury endosperm are very rapidly fermented, increasing the risk of acidosis. This might explain why water deprivation or altered drinking patterns often increases the incidence of acidosis in feedlots.

Greater in situ disappearance of floury than vitreous starch hybrids has led to the suggestion that extent of digestion is greater for hybrids containing more floury and less vitreous endosperm when the grain is rolled (not extensively processed). This concept is supported by results from feeding trials Jaeger et al. (2004); maize hybrids with a higher proportion of floury starch produced the best gain efficiency (r = 0.83) when dry rolled. So for rolled or ground grain, more floury grains will have greater starch digestibility. However, floury grains have disadvantages for flaking, yielding more fine particles and fragile flakes; floury hybrids also tend to flake less rapidly and less consistently than more vitreous hybrids. Fermentation also can influence vitreousness. When subjected to fermentation as part of maize silage, the proportion of vitreous starch in maize kernels declined (Johnson et al., 2002). Similarly, when high moisture maize was prepared from grain hybrids that were either more vitreous or floury when the grain was mature, ruminal and total tract starch digestibility by steers of starch tended to be superior for the vitreous, not the floury, hybrid (Szasz et al., 2007). Flaking grains also eliminated effects of starch vitreousness on starch digestibility in a trial by Corona et al. (2006). Thus, the advantage in starch digestibility seen with more floury (less vitreous) maize grain that is detected when grain is dry rolled no longer applies when the grain is fermented or flaked.

Resistant starch. With exposure to heat and moisture during flaking, starch granules swell and form gels, a process called gelatinization. Swollen particles become enriched in amylopectin as amylose diffuses out of the swollen granules. Upon cooling of gelatinized starch, the amylose will gel and form retrograde starch, one of three different types of “enzyme-resistant starch.” Slow cooling of flaked maize grain

decreases “starch availability,” a commercial index of susceptibility of starch to a starch degrading enzymes (i.e., amyloglucosidase). Ward and Galyean (1999) measured in vitro dry matter disappearance of flaked maize samples that had been held warm. Even though starch availability was decreased by one-third, presumably due to starch retrogradation, rate and extent of in vitro digestion was no lower for flaked maize that had decreased starch availability and presumably contained retrograde starch. Until further information on nutritional value of flaked grain becomes available, rapid cooling of flakes to avoid starch retrogradation would seem wise.

Implications. To select the most desirable processing method, the enhancement in the NEg value of grain processed by various methods must be balanced against the fixed and variable costs involved with handling and processing the grain as illustrated in reports from Macken et al. (2006) and Peters (2008). Equipment for flaking typically is huge and expensive; this has limited installation of flakers to larger feedlots or to milling operations that can market flaked grain to multiple users (e.g., dairies). With flaking, continuing overhead costs for personnel and maintenance also must be considered. Based on responses to flaking by various grains (greater benefit with dent maize than for small grains; greater benefit from sorghum than dent maize grain; equal starch digestibility after flaking maize grain samples that ranged from 55 to 65% vitreous starch), NEg improvements from flaking maize presumably will be even greater for flint than for dent maize grain. However, direct comparisons are not yet available for full economic comparisons. Feedlot consultants in the US on the average assume that the NE value of dent maize is increased by an average of 10.9% by steam flaking though different consultants rate this advantage from 2.5% to 19%! Based on direct comparisons from feedlot trials, the mean advantage in NEg from flaking is about 18% (Zinn et al., 2002). Results from digestion trials alone, though supporting an advantage for flaking, cannot fully explain the increased NEg of flaked grain apparent from animal performance trials. Indeed, well flaked maize and high quality high moisture fermented maize have equal digestibility for starch and dry matter, but the NE value calculated from cattle performance consistently is greater for flaked maize. Consequently, factors beyond starch digestibility that are associated with efficiency of fermentation or metabolism (energy losses as methane, heat, urine, or feces at high

intake levels; compensatory fiber digestion in the large intestine) probably are responsible for these extra-caloric effects observed with flaked maize. Nevertheless, fecal starch concentration, though more complex than laboratory evaluations, appears to be reliable as an index of the response to and consistency of processing within a processing method and can prove useful to predict NEg value of a processed grain (Zinn et al., 2007). For continuous monitoring of flake quality, flake density measured at the steam flaker when conducted using a standard, repeatable technique (hot, moist flakes) appears useful.

PROTEIN SUPPLEMENTS

Finishing diets at feedlots served by consulting nutritionists contain an average of 13.3% crude protein (range of 12.5 to 14%) with 1% urea (range of 0 to 2%). For the one-third of consultants who employed this measurement, ruminally digested intake protein (DIP) was maintained at an average of 8.5% of diet dry matter (7 to 9.5%).

Ruminants obtain amino acids from two sources: 1) dietary protein or amino acids that escape fermentation in the rumen, often called unfermented intake protein (UIP) and 2) protein synthesized from DIP including non-protein nitrogen by growing and multiplying ruminal microbes. Microbial protein alone provides an adequate supply and balance of amino acids for concentrate-fed cattle with a body weight over 300 kg, so the primary concern for larger feedlot cattle is supplying an adequate amount of DIP to keep ruminal microbes active in digesting feed components. Supplemental DIP for feedlot diets can be supplied at least cost from urea or ammonium salts; feedstuffs and byproducts rich in protein as well as ammonia recycled to the rumen also supply DIP. For cattle less than 300 kg in weight, high bypass proteins balanced in amino acids (rich in lysine to supplement most cereal grains or in methionine to supplement microbial protein) often improves performance and animal health. However, the depressed rate of gain by calves less than 300 kg that are marginally protein-deprived or amino acid deficient typically is only temporary; deprived calves exhibit compensatory growth at heavier weights. So feeding supplemental bypass protein or rumen-protected amino acids usually is not economical based on weight gain responses alone. However, effects of early protein deprivation on animal health or on body composition and efficiency for the full feeding period have not been examined thoroughly.

Microbial protein synthesis in the rumen, and thereby the microbial need for ammonia, generally is limited by the supply of energy (ATP) available for microbial growth. Consequently, the requirement for supplementing DIP for ruminal microbes depends on two factors – the supply of ruminally fermented carbohydrate and the supply of DIP provided by diet ingredients. Grain processing methods that increase the extent of ruminal starch digestion (flaking, high moisture grains) increase the need for DIP. In addition, through denaturing grain protein, flaking increases ruminal protein escape, further elevating the need for DIP. Although performance responses to dietary DIP concentrations have lacked consistency (Figure 5), it seems logical that grain processing should alter DIP requirements; predicted DIP requirements are considerably lower for diets based on dry rolled than on steam flaked or high moisture maize (6.5 versus 8.2 and 9.4% dietary DIP, respectively) due largely to differences in ruminal availability of starch.

Responses to protein levels over 11% seldom are seen with calves weighing over 400 kg. Certainly, calves will have greater demand for amino acids for growth than older cattle. But if feedlot diets are formulated to meet DIP requirements alone, protein requirements would not be expected to decline drastically as cattle gain weight unless the extent or efficiency of recycling of urea to the rumen is greater for larger, heavier cattle. Nevertheless, for performance of cattle over 400 kg, crude protein concentrations below 11% of diet DM appear adequate. Though economically desirable and environmentally preferable, decreasing the protein content of diets for heavier cattle is infrequently practiced at commercial feedlots due to logistical limitations, e.g., formulating and managing additional diets; wide distribution in both current and mature weights of cattle within a pen.

Ruminal ammonia concentrations and blood urea concentrations below 10 mg/dl and 10 mg/100 ml, respectively, often are used as clinical indices that a diet contains an inadequate amount of dietary DIP. In addition to supplying DIP for ruminal microbes, ammonia generated from DIP acts as a base at the pH of the rumen and may improve acid-base status of the animal. Readily released from urea in the rumen, ammonia rapidly absorbed from the rumen can cause urea (ammonia) toxicity. Likelihood of toxicity is greatest when diets or supplements contain a high amount of urea, are low in energy (and thereby ruminal pH is high), and are fed infrequently. Concerns about urea toxicity have stimulated extensive research with compounds or complexes that

release ammonia at an attenuated rate. Yet, no benefit from slow release compounds has ever been demonstrated with feedlot cattle. Several factors may be involved. First, ruminal pH typically remains below 5.8 for cattle fed high concentrate diets, and low ruminal pH retards ammonia absorption. Second, feedlot cattle typically consume 4 or more meals each day spread through the day and have a ruminal liquid mass that exceeds 30 kg. These factors attenuate spikes in ruminal ammonia concentrations. Third, feedlot cattle usually are fed totally mixed rations; this reduces the likelihood that animals can consume a large amounts of urea abruptly. Because they totally resist both fermentation and digestion, some attenuated ammonia release compounds widely marketed are useless for ruminants except for avoiding ammonia intoxication!

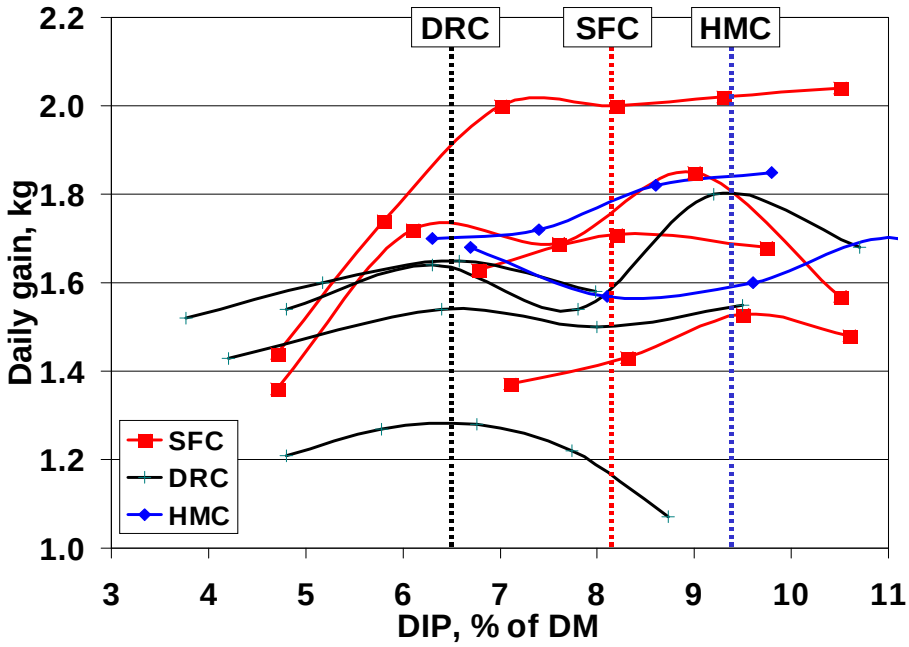

Figure 5 - Feeding trial responses to dietary DIP concentrations with dry rolled (DRC), steam flaked (SFC) and high moisture maize (HMC).

VITAMIN SUPPLEMENTS

Vitamins and minerals typically are included with the liquid, granular, or pelleted protein supplement being supplied to feedlot cattle. According to consulting nutritionists, feedlots provide supplements either as dry pellets (39% of consulting nutritionists), as liquids (45%), or as granular feeds mixed with the total diet. Micronutrients also can be mixed with water and sprayed onto diets (49% of consulting nutritionists). Although many cattle receive injections of vitamins A and E at the start of their feeding period, consulting nutritionists supplement feedlot diets with an average of 5200 IU vitamin A (range of 2200 to 11,000), 330 IU vitamin D (range of 0 to 1100), and 26 IU vitamin E (range of 5 to 110) per kg of diet. Recently, concerns have been raised that excessive vitamin A intakes may retard marbling. Vitamin D is supplemented for cattle not exposed to sunlight; feeding high doses of D for a few days before harvest may improve tenderness of beef cuts. For the water soluble vitamins, performance responses to supplementation are very rare, perhaps because all B-vitamins are synthesized by ruminal bacteria and most unprotected B-vitamins are degraded readily by ruminal microbes. However, thiamin supplementation (up to 1 g per animal daily) has been suggested to reduce the incidence of polioencephalomalacia among cattle, a condition observed when sulfur intakes are excessive (above 0.5% of diet dry matter).

MINERAL SUPPLEMENTS

Dietary requirements for minerals have been studied widely; most nutrient requirement tables provide lists indicating both mineral requirements and maximum tolerance levels. Target levels used by consulting nutritionists are contrasted with mineral requirement and maximum tolerance estimates from NRC (1996) in Table 1.

Table 1 - Survey results versus NRC (1996) mineral requirements for feedlot cattle

Macro-minerals	Ca	P	Mg	K	S	Salt	
Survey, %	0.70	0.30	0.22	0.70	0.22	0.30	
Range	0.6-0.9	0.16-0.45	0.15-0.4	0.5-0.8	0.15-0.4	0.15-0.5	
NRC (1996), %	0.44[b]	0.26[b]	0.10	0.60	0.15	0.15	
Max tolerance	1.80	-	0.40	3.00	0.40	-	
Trace minerals	**Cu**	**Zn**	**Mn**	**Fe**	**Se**	**I**	**Co**
Survey, ppm	18	93	48	52	0.24	0.75	0.38
Range	10-40	40-212	20-80	5-150	0.10-0.6	0.10-2.3	0.10-1.5
NRC (1996), ppm	10	30	20	50	0.10	0.50	0.10
Max tolerance	100	500	1000	1000	2	50	10

[a] From Vasconcelos and Galyean, 2007.
[b] 250 kg steers gaining 1.5 kg daily.

Because grains are low in calcium, diet supplementation with calcium carbonate, a low-cost, readily available source, is common. Most concentrate diets contain adequate amounts of ruminally-available phosphorus so that phosphorus does not need to be supplemented to the diet. Indeed, 83% of feedlot consultants did not supplement feedlot diets with phosphorus. However, potassium (as the chloride, carbonate, bicarbonate) and sodium chloride (salt) are commonly supplemented (Table 1). When urinary calculi incidence is a problem, supplemental salt may prove beneficial, but in general the level of salt being fed is excessive. To reduce environmental accumulation, some feedlots now include less than 0.15% salt in diets for finishing cattle. Trace mineral target levels being fed generally exceeded the requirements of feedlot cattle proposed by NRC (1996) to a slight degree. Ruminants lack the nutritional sense to select their own supplemental minerals despite claims of salespeople that sources of individual minerals should be provided. To improve bioavailability of the trace minerals zinc, copper, and selenium, these minerals often are chelated with amino acids, protein, or other organic substances. Though mineral bioavailability may be greater, organically complexed minerals are more costly than inorganic mineral sources and very few research trials with feedlot cattle have demonstrated any advantage in performance or efficiency for substituting chelated or organic minerals for inorganic mineral sources.

DIGESTIVE AND METABOLIC DISORDERS

Within the US, most morbidity and mortality of feedlot cattle is attributed to bovine respiratory disease, a viral infection readily transmitted among cattle that subsequently will involve various bacteria. Two approaches are used for treatment of bovine respiratory disease – individual animal treatment or mass medication where all animals receive medications. Diagnosis, based on animal appearance, requires skill. When diagnosis is confirmed by detecting an elevated rectal temperature (above 40 C), treatment typically involves dosing with sulfa drugs and antibiotics cleared by governmental agencies and monitoring body temperature daily and switching drugs daily until fever declines. If skilled labor for diagnosis and treatment is not available, mass medication, albeit more costly, is a useful alternative.

Acidosis is the most common digestive tract disorder of ruminants fed high concentrate diets (Owens et al., 1998). Acid accumulation within the rumen is responsible for this condition that, based on pH of ruminal contents, is denoted as clinical acidosis (pH below 5.2) or sub-clinical acidosis (pH between 5.2 and 5.5). Ruminal pH is depressed when ruminal acids, in many cases lactic acid, accumulates. With sub-clinical acidosis, feed intake will be irregular and performance is depressed, but with clinical acidosis, the rumen wall is damaged and death can occur due to blood acidity. The low pH and high osmotic pressure of rumen contents cause erosion of the ruminal wall. When rumen bacteria Fusobacterium necrophorum enter the blood stream, they travel to and embed in liver tissue causing an abscess to develop (Nagaraja and Chengappa, 1998). Consequently, animals that experience acidosis have a higher incidence of liver abscesses. In addition, hoof damage often is associated with acidosis, but the culprit there appears to be histamine that occasionally is produced in the rumen. Acidosis occurs most frequently when animals unaccustomed to high concentrate diets consume a large amount of starch. Thus, the adaptation period when cattle begin to consume high concentrate diets is particularly hazardous. Liver abscesses incidence and severity are reduced by half (from an industry average of about 15%) by supplementing diets with one specific antibiotic (tylosin) that inhibits growth of Fusobacterium necrophorum. Other antibiotics such as Virginiamycin and monensin help control the population of acid-producing ruminal microbes, and inoculation with lactate-using bacteria (Megasphera, Propionibacteria) hold promise for

reducing the incidence of acidosis. Vaccines and monoclonal antibodies for control of the bacterial pathogens currently are being tested. In some regions of the US, liver abscesses do not occur, perhaps related to absence or low prevalence of specific ruminal bacteria or certain fungi that exacerbate this problem.

Feedlot bloat is most prevalent when small grains (wheat, barley) are fed (Cheng et al., 1998). Due to accumulation of free gas in the rumen (not the frothy foam associated with legume and wheat pasture bloat), feedlot bloat can reflect physiological abnormalities of individual animals or some physical or physiological factor that inhibits the eructation process. Feeding monensin reduces the incidence of feedlot bloat but specific reasons for this response are not clear.

Lung lesions are detected at harvest for a substantial percentage (up to 50%) of feedlot cattle (Gardner et al., 1999). In some cases, these lesions are residues from bouts of bovine respiratory disease or from sub-clincal cases of pulmonary emphysema. If lung capacity is reduced markedly, performance and quality grade often are reduced but no specific cause or remedy for lung has been isolated. Mass medicating all animals for bovine respiratory disease, rather than waiting for overt symptoms, should reduce the incidence of lung lesions.

Other feedlot digestive disorders including polioencephalomalacia (Gould, 1998), urinary calculi, and the interactions of nutrition with cattle health and immunity have been described elsewhere (Galyean et al., 1999). For extensive discussion of the etiology, incidence, and feedlot practices that may reduce the incidence of such disorders, readers are directed to these sources or veterinary texts and reports.

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